CONGESTION MANAGEMENT OF TRANSMISSION NETWORK USING STATCOM

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ELECTRICAL ENGINEERING

May, 2013

Congestion Management of Transmission Network Using STATCOM

BY

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A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

ELECTRICAL ENGINEERING

May, 2013

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

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إهداء

بسم الله الرحمن الرحيم

وَقُل رَّبِّ زِدْنِي عِلْمًا (سورة طه – أية 114)

أهدي هذه الرّسالة ،،

إلى **والدتي** - رحمها الله وأسكنها فسيح جنانه -

التي تعبت في حملي وتربيتها الصالحة ودعائها المستمر لي بالتوفيق

إلى **والدي** - حفظه الله ورعاه -

لتربيته الصالحة ودعمه المستمر وحرصه على تعليمي

إلى **خالتي نادية** - حفظها الله ورعاها -

أمي الثانية لدعمها ودعائها المستمر

إلى **إخوتي** و **أخواتي**

لمساندتهم وتشجيعهم الدائم

ACKNOWLEDGMENTS

Praise and glory to Allah the most gracious and merciful, who gave me courage and patience to carry out this work. Peace and blessing of Allah be upon last Prophet Mohammad (Peace be upon Him).

I would like to express my deep appreciation to my thesis advisor Professor Ibrahim M. El-Amin, for his guidance, encouragement and continuous help throughout this work. Thanks also are due to my thesis committee member Professor Mohammad Ali Y. Abido and Doctor Ali Al-Awami, for their cooperation and help.

Acknowledgment is due to King Fahd University of Petroleum and Minerals for supporting this work.

Many thanks and appreciation are due to National Grid – Saudi Arabia Company, EOA and all its staff members who provided support to complete this work, especially System Operation and Control Department.

I also acknowledge my father Dr. Ibrahim Yousif Al-Hamoudi and Engr. Abdulaziz A. Al-Nuaim for their support for this work.

Finally, I extend my acknowledgment to my parents, brothers and sisters and my friends who supported my through this work.

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LIST OF APPREVIATIONS

MCP	:	Market Clearing Price
ISO	:	Independent System Operator
MP	:	Market Participants
FACTS	:	Flexible AC Transmission System
STATCOM	:	Static Synchronous Compensator
SVC	:	Static Var Compensator
MD	:	Market Dispatch
CR	:	Congestion Re-dispatch
IGO	:	Independent Grid Operator
SMP	:	System Marginal Price
TCSC	:	Thyristor Controlled Series Compensator
UPFC	:	Unified Power Flow Controller
OPF	:	Optimal Power Flow
SRP	:	System Re-Dispatch Payment
LMP	:	Location Marginal Price

ABSTRACT

Full Name : Abdulaziz Ibrahim Alhamoudi

Thesis Title : Congestion Management of Transmission Network Using STATCOM

Major Field : Electrical Engineering

Date of Degree : 2013

Congestion management in transmission network utilizing STATCOM incorporation in transmission network is presented. Transmission congestion management problem is studied from different aspects, i.e. congestion relief, location marginal price reduction, congestion costs and cost recovery period are carried out. Genetic Algorithm as an intelligent optimization technique is considered to obtain the optimum STATCOM location and rating to be incorporated in the transmission grid. Comparisons with similar results reported in literature are demonstrated. The effectiveness of STATCOM installation in a congested transmission network to enhance power flow parameters and to maintain location marginal prices at acceptable levels is verified

ملخّص الرسالة

الاسم: عبدالعزيز ابراهيم يوسف الحمودي

عنوان الرسالة: إدارة اختناقات شبكات نقل الطاقة باستخدام معّوض القدرة المتزامنة غير الفعّالة

التخصص: الهندسة الكهربائيّة

تاريخ الدرجة العلمية: ذو القعدة 1434 هـ

تختلف طرق التّعامل مه الاختناقات في شبكات نقل الطّاقة في أسواق الطأقة المختلفة ، معظم أسواق الطّاقة طوّرت طريقة للتعامل مع الاختناقات وكيفيّة فوترتها ، وان كانت النتيجة المشتركة في معظم الحالات حل مزقّت وارتفاع سعر الطّاقة الكهربائية للمستهلك.

يتلخّص هذا البحث في استعراض الطرق المستخدمة عالميا لإدارة الاختناقات الكهربائية والعوامل المؤثرة في فوترتها. و يقدم البحث دراسة إدارة اختناقات شبكات نقل الطاقة باستخدام **معّوض القدرة المتزامنة غير الفعّالة** وتأثير استخدامها في تشغيل الشبكة من عدّة نواحي مثل: فك الاختناق في الشّبكة، الفوترة، تقليص التكلفة النّاتجة عن الاختناق. ويتم خلال هذا البحث دراسة مبنيّة على تركيب العدد والمكان الأمثل من معوّضات القدرة المتزامنة غير الفعّالة في شبكة النّقل بالإضافة الى حجمها. ويقدم دراسة جدوى مبنيّة على التوفير المادّي من اختناقات الشّبكة بعد تركيب معوّضات القدرة المتزامنة غير الفعّالة.

ويتم تقديم مقارنة نتائج الدراسة مع بحوث سابقة على شبكات كهربائية أصغر حجما من الشبكة في هذا البحث. بالإضافة الى مقارنة بين استخدام معوّضات القدرة المتزامنة غير الفعّالة و معوّضات القدرة الاستاتيكيّة غير الفعّالة في تأثيرها على الاختناق في شبكة نقل الطّاقة.

CHAPTER 1

1. INTRODUCTION

1.1 Introduction

After producing efficient and improved in telecommunication and airways industries, many electric utilities adopted the idea of deregulation since 1990's. Generation, Transmission and Distribution companies are, in vertically-integrated structure, usually owned by the government. Whatever expenditure or revenue of the power system operation will be covered and earned by the government.

Deregulation of power system can be defined as a restructuring of rules and economic incentives that government set up to control and drive the electric power industry. This means that the system will have open access in terms of power generation and distribution that may result in a competitive market in power industry. In deregulated environment Generation, Transmission and Distribution may be owned and operated by different organizations. The concept of optimizing operation in terms of expenditure and revenue will be the main base on which the organization will rely. Agreement between Generation and Distribution companies are made in advance to maintain coordination.

By the time of power delivery implementation, transmission loading patterns are different from what they were planned to be. Transmission system operator (TSO) must assure open access to transmission networks to all operational market participants. However, congestion in transmission network may occur when producers and consumers of electricity tend to exchange power that operates transmission networks beyond one or more operation limit.

Congestion management is controlling transmission system in a way that limits are not violated. This means that system security and reliability are within acceptable range. Transmission limits may refer either to a piece of equipment that limits power flow in physical terms, or to operational limit that could be violated. The violation of transmission constraints will be reflected in the economics of the power network in a variation of the cost of electric energy. The basic objective is to control generator output so that the system remained secure –no limit violation- at the lowest cost. However in a deregulated environment, the goal is to create a set of rules that ensures sufficient control over produces and consumers to maintain an acceptable level of power system in both short (real-time operation) terms and long (transmission and generation construction) while maximizing market efficiency.

Congestion in transmission system could be treated in several ways such as:

- Load Shifting.
- Generation Re-dispatch.
- Contracts curtailment.

All solutions of congestion situations differ in their approach. They all give a temporary solution to the market problem which would not be sufficient to as a long-term solution. Transmission expansion in a rapidly growing environment would be a smart solution if it is associated with economic revenue that would attract investors. Moreover, system reliability and security would be enhanced as the system expands.

1.2 Energy Pricing In a Deregulated Electricity Market

The cost of energy in open markets is usually determined through the following process: First, the load of any power system is forecasted, as such in open markets. Then, generation companies offer their willingness to sell to the market. The market coordinator will select the least cost generators to be used. At this stage, the preliminary price of energy is known. This is called Market Clearing Price (MCP) stage. Afterwards, Independent System Operator (ISO) simulates load flow with all limitations in the power system and defined constraints to check the visibility of the selected generators. If no congestion occurs, the following will be added to the MCP: power transmission system losses; ancillary services; transmission usage tariffs and other taxes.

However, if congestion appears such as overloading, over and under voltages, stability violation or security violation, adjustments of the market dispatch will take place till it satisfies the power system constraints. Adjustments may include reducing selected generators, increasing other generators, running an expensive generator which were not selected in MCP stage, shutting down cheap one, …etc. After satisfying all system constraints, the price of energy will be recalculated to include the new set of generators plus transmission charges.

It can be observed from international practices that congestions in electric power delivery process are circumstantially resolved. For transmission companies, system expansion would be a key solution to resolve congestions. Since transmission revenue is usually slower than those in generation and distribution, transmission investments are not attractive to investors.

For transmission expansion, the economic revenue should be defined on the basis of system relief to reflect what a project has provided the system with. In order to formulate the incentives for transmission expansion investors, each system should be seen from ISO point of view, and the incentive formula should depend on some of the following: How much is the reliability improved? How much is the power price reduced? And how many more problems will the expansion resolve?

1.3 Thesis Motivation

The research shows that congestions in transmission networks can be solved in different ways. There is no certainty on which approach would result in best solution in terms of congestion relief and reliability increase beside the financial revenue for investors. Thus, there is a need to find a method that has the following features:

- Congestion relief.
- Transmission expansion.
- All market participants (MP's) contribution to transmission expansion, similar to generation expansion.
- System security and reliability enhancement.
- Reducing congestion costs.

1.4 Thesis Objective

This thesis is dedicated to resolve of transmission congestion through expansion and revenue process from Transmission Company's point of view. The goal of this expansion is to reduce congestion costs, mainly congestion re-dispatch payments, reduction and maintaining energy prices. The method is examined by utilizing STATCOM in power system network expansion.

1.5 Thesis Organization

This thesis consists of six chapters. It starts with an introduction. Chapter two provides a literature survey of congestion management techniques utilizing several FACTS controllers. Problem formulation and methodology are presented in chapter three. A case study of an ideal Middle-Eastern 16-bus 380KV system is presented in chapter four. Application of STATCOM for Congestion Elimination is presented in chapter five. Studies on the application of STATCOM and SVC in congestion management are presented in chapter six. Finally, the conclusions will be presented in chapter seven.

CHAPTER 2

2. LETERATURE REVIEW

2.1 Congestion Management Models

There are several forms of deregulated electric power industry. They differ in each area in details of implementation. These forms can be represented in five main models that are; United Kingdom and Wales, Pennsylvania-Jersey-Maryland (PJM), Norway, Sweden and California [1].

2.1.1 England and Wales Market

In England and Wales market, only one zone exists and no constraints are considered in market dispatch (MD) stage. In this stage the zonal price, System Marginal Price (SMP), is determined from generators offers [2]. In congestion re-dispatch (CR) stage, all constrains are considered and every bus in the system becomes a zone. Generators are commanded to adjust their generation by the Independent Grid Operator (IGO) and receive compensation for doing so. Loads are considered to be fixed and do not participate in both stages.

Energy price is set at MCP stage according to generators offers. Additional charges, called “uplift”, i.e. charges for losses and ancillary services, are passed to the consumers.

“Constraint off” occurs when a generator was on in MD stage and instructed by IGO to be off in CR stage. “Constraint on” occurs when a generator was off in MD stage and instructed to be on in CR stage. For “constraint off” case, generators will receive “lost profit” as a compensation and for “constraints on” case, generators will be paid its offer price.

2.1.2 Pennsylvania-Jersey-Maryland (PJM)

PMJ market would be considered as the ultimate case of zonal partitioning, where each node is a zone with its own zonal price and each line is an inter-zonal interface. The conceptual basis of the “price-based” dispatch is an optimization framework in which the nodal prices can be determined as dual variables according to specific constraints. All calculations are conducted in the MD stage using the state estimator data [3]. CR stage is not needed since all constraints are considered in MD stage.

The dual variables output for each node of the optimized framework are the buy and sell prices and the difference in each node pair is the transmission usage charges that will be paid back to transmission investors.

2.1.3 Norway:

In the MD stage, for each hour, the Independent Grid Operator (IGO) uses the forecasted operational state of the grid to determine whether a partition of the grid into zones is required [4]. In MD sage, the grid-wise, in case of one zone, or each zone clearing price is determined. If the grid is divided into zones the tie-lines limits between zones are considered as constraint in MD stage as well. During CR stage, if needed, the participants are adjusted according to their adjusting bids and offers. In this stage each bus is considered a zone.

As mentioned the MCP is set at MD stage, any adjustment payment might result from CR stage will be added uniformly. Upward adjustment is paid the most expensive bid/offer price and downward adjustment is charged the cheapest offer price.

2.1.4 Sweden:

In Sweden, the same rules apply as Norway with one major difference. The IGO considers only one zone in MD stage as in England and Wales market. On the other hand, Norway market considers several nodes at MD stage.

2.1.5 California

The IGO in California uses a predefined set of zones [5]. The MD stage establishes the hourly market zonal prices for the next day market. In the MD stage the transmission constraints are not considered, the resulting prices are simply the solution of preferred schedules introduced by scheduling coordinators in bilateral markets. If the MD solution leads to congestion, the elimination will be achieved using CR with zonal partitioning.

The CR stage gives the zonal prices and the transmission usage prices as dual variables associated with the interface flow. Participants will be paid and charged according to zonal prices defined in CR stage. Congestion charges are applied using the transmission charges in the inter-zonal interface.

2.2 Flexible AC Transmission System (FACTS)

Flexible AC Transmission System (FACTS) is an alternating current transmission system incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability [6]. FACTS devices have become very important applications of power electronics in adjusting power flow by controlling any of the AC transmission system parameters, namely, voltage magnitude and phase and load impedance. The main objectives of FACTS are to increase transmission capacity of lines and to control the power flow over chosen transmission routes [7].

The static synchronous compensator (STATCOM) is one of the most prominent members in the family of FACTS devices, which is connected in shunt to the transmission grid [8]. It senses the AC system terminal voltage and compensate for the voltage difference across the coupling transformer connecting it to the AC system by exchanging reactive power. If the output voltage is greater than the AC voltage, it supplies reactive power to the AC system and it absorbs reactive power if the output voltage is less than the AC voltage [9].

2.3 Congestion Management Utilizing FACTS Devices

Different approaches have been proposed in congestion management. The objective of these approaches is to resolve congestion in electricity market such that no security limit is violated and to minimize economic aspects in terms of congestion costs. Utilizing different types of FACTS in congestion management were proposed with different approaches.

A cost-free congestion relief using FACTS in power transmission network was suggested in [10]. It proposed an analysis to be done by ISO ahead of time to ensure system security using optimum power flow (OPF) in the current supply and demand. Once congestion is observed, the ISO has to relieve it using one of two types:

A. Cost-free means:
   1. Out-going of congested lines.
   2. Operations of transformers tap/phase shifters.
   3. Operation of FACTS devices particularly series devices.

B. Cost-associated means:
   1. Re-dispatch of generation to modify power flow in transmission system.
   2. Curtailment of loads (load-shedding).

The author suggested a cost-free congestion relief by utilizing Thyristor Controlled Series Compensator and Unified Power Flow Controller optimum allocation using Genetic Algorithm technique subjected to all system parameters limits (V, Pg, Qg, etc...). The results were found to be satisfying. However, the congestion relief was temporarily for the existing supply and demand and does not take into consideration load growth rate and congestion due to transmission system forced outage.

The placement of TCSC has also been incorporated to observe the impact on LMPs difference and congestion rent [11]. The proposed methodology is tested and validated for locating TCSC in IEEE-30 and IEEE-57 bus systems. Results showed that the proposed method is capable of finding the best location if TCSC installation that suits both objectives.

An approach to maximize the benefits of FACTS installation in power system for an efficient solution to congestion management in bilateral electricity markets is presented in [12]. Minimizing congestion cost is examined using the optimum location and ratings of installing STATCOM and UPFC about congested lines. Preliminary results have shown that the method is able to effectively determine the optimum location to minimize congestion costs using a 4-bus system. The case study case has indicated that a STATCOM is a viable economic solution to the congestion management problem in bilateral electricity market environments.

Incorporation of FACTS to enhance power system security in deregulated environment is presented in [13]. The objective is to identify the optimal location and capacity of STATCOM to enhance voltage security and find the capacity of a properly placed Unified Power Flow Controller to manage transmission network congestion simultaneously. An artificial intelligence method is used to solve the problem. The method is implemented on a modified IEEE-14 bus case study and results show the effectiveness of the proposed algorithm.

2.4 Optimal Power Flow (OPF)

The goal of optimal power flow (OPF) is to minimize the costs of meeting the load demand for a power system while maintaining the security of the system. The costs associated with the power system may depend on the situation, but in general they can be attributed to the cost of generating power (MW) at each generator. OPF will perform all the steady-state control functions of the power system. These functions may include generator control and transmission system control. OPF also determines system marginal cost data (LMPs). This marginal cost data may aid in the pricing of MW transactions as well as the pricing ancillary services such as voltage support through MVAR supply [14].

Congestion Management and transmission price determination in electricity market using OPF is presented in [15]. The congestion management is based on optimal power flow, whose main goal is to obtain a feasible solution for the re-dispatch minimizing the changes in dispatch proposed by the market operator. The computation considers the physical impact caused by the market agents in the transmission network. The final tariff includes existing system costs and costs due to the initial congestion situation and losses. The proposed method is simulated on IEEE-30 bus power system.

Different approaches were used to relieve a congested power transmission network such as constructing new transmission lines, installing FACTS controllers and bilateral contracts. These approaches aim to relieve the power flow in transmission network considering several aspects such as network security, reliability and power prices.

The literature survey reveals that utilizing FACTS controllers in congestion management studies has shown a success in congestion relief. Moreover, combination between series and shunt compensation has been used to enhance bus voltages and transmission line power transfer capability. Also, utilizing FACTS controllers in congestion management have shown a success in obtaining congestion revenues.

However, the effect of FACTS controllers are tested on a small systems and the studies concentrated on generation re-dispatch rather than expanding transmission network. A study on large-scale congested network study is needed to support the conclusion of previous studies. Furthermore, determining the optimum location and rating of FACTS, to be installed in the transmission network, may increase congestion revenues and as a result will minimize the economical profits of congestion management.

Chapter 3

3. System Modeling and Methodology

3.1 Problem Description

Power system under deregulated environment is usually operated by Independent System Operator (ISO). The prime duty of the ISO is to maintain system security with least possible cost of energy. In many markets, for example United States, electric power trades are processed through market operator. Thus, the ISO is not involved directly with contracts executions. In some US states, it is even against the law to communicate outside the formal channels. This will result in reducing operators market power.

To study and propose a solution to congestion relief in a certain system, it is necessary first to define the ISO duties and responsibilities: How the ISO looks at the power system? How do electric power prices are set? And how to deal with a congestion if it occurs in a power transmission network?

The ISO deals with real time system status which does not remove the congestion permanently. Most congestion requires investment in equipment installation. The permanent correction of congestion under deregulated environment is not clearly defined.

In this thesis, a mechanism for permanent congestion relief is presented from transmission network owner's perspective. The mechanism is based on the addition of a number of Static Synchronous Compensators (STATCOM) to the transmission network. The main goals of the technique are:

1. Find the optimum locations and ratings of STATCOMs installed based on minimizing reactive power loss and enhancing voltage profile as caused by loaded elements subjected to all power system constraints.

2. Relieve congestion by installing STATCOMs in a way that will attract investors to participate in power transmission system by providing revenue from this investment.
3. Enhance power system security and reliability in case of forced outage or tripping situation.
4. Reduce generation re-dispatch costs that will be paid by transmission owners to generation companies.

3.2 Modeling

3.2.1 Static Synchronous Compensator (STATCOM)

The static synchronous compensator (STATCON) is one of the most prominent members in the family of FACTS devices, which is connected in shunt to the transmission grid [16]. It is usually used to control transmission voltage by reactive power compensation. In ideal steady state analysis, it can be assumed that active power exchange between the AC system and STATCOM can be neglected, and only the reactive power can be exchanged between them.

The presence of FATC controllers is accommodated and accounted for by adding new equations to the set of the power flow formulations and modifying some of the existing power flow equations, as needed. The Jacobian equation is modified accordingly [17]. Figure 3.1 shows the circuit model of a STATCOM connected to Bus k of an N-Bus power system: the subscript ‘p’ means the STATCOM is connected in parallel with the power system. The STATCOM is modeled as a controllable voltage source (E_p) in series with impedance.

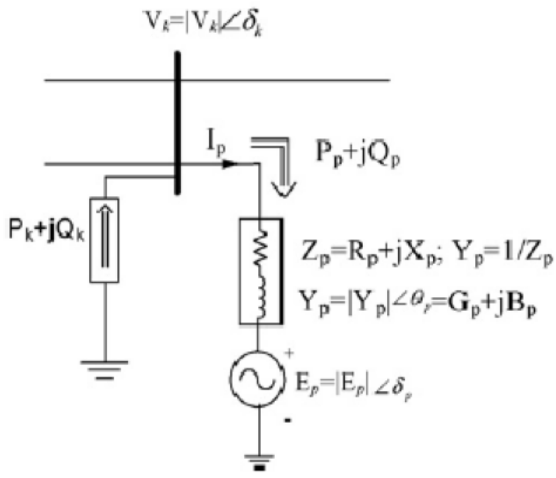


Figure 3.1 STATCOM Model

The power flow equations for all buses of the power system without FACTS controller will be the same except at the bus k which containing STATCOM which will be:

$P_p = G_p\ |V^2{}_k| - |V_k|\ |E_p|\ |Y_p| \cos(\delta_k - \delta_p - \theta_p)$

(3.1)

$Q_p = -\ B_p\ |V^2{}_k| - |V_k|\ |E_p|\ |Y_p| \sin(\delta_k - \delta_p - \theta_p)$

(3.2)

Where,

V_k is the voltage at bus k

δ_k is the angle at bus k

$|E_p|$ is the generated AC voltage from STATCOM converter,

δ_p is the angle of generated AC voltage from STATCOM converter,

$|Y_p|$ is the admittance magnitude of STATCOM connected to bus p, and

θ_p is the admittance angle connected to bus p.

STATCOM cost is estimated at 50$/KVAR [18]. This cost will be considered in calculation of capital cost of STATCOM in the study. Consequently, revenue analysis will be conducted based on the assumed STATCOM cost.

3.2.2 Static Var Compensator (SVC)

Static Var Compensator is a FACTS device based on thyristor controlled reactor [19]. It consists of standard reactive power shunt elements which are controlled to provide rapid and variable reactive power (supply or absorb) [20]. Figure 3.2 shows SVC typical model.

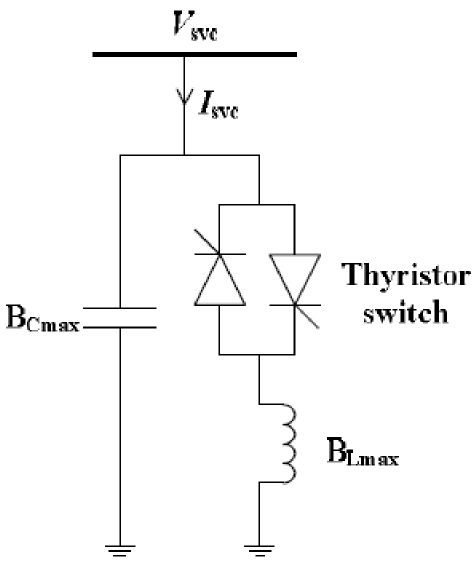


Figure 3.2 SVC Model

The power flow equations for all buses of the power system without FACTS controller will be the same except at the bus k which containing SVC which will be [21]:

$$Q_p = - B_{SVC} V^2_k \tag{3.3}$$

Where,

V_k is the voltage at bus k, and

B_{SVC} is the suseptance of the SVC.

SVC will be included in the study in the application of FACTS controllers in transmission congestion management.

3.2.3 Congestion Cost Calculation Approaches

Congestion costs can be obtained from the following three approaches [22]:

1. **Uplift Charges**

Uplift charges are equal to the increased dispatch payments by the market to generators that are out of merit order. It suppresses the difference in LMP's between two areas and it is collected by the transmission owners.

2. **System Re-Dispatch Payments**

System re-dispatch payments are equal to the difference in dispatch payments by the market to generators in congestion case relative to the costs for the uncongested case.

3. **Congestion Revenues**

Congestion revenues are the evaluation of transmission of energy across a congested interface. Including losses, the revenues are equal to the product of energy flow multiplied by the price of LMP at that congested zone. Congestion Revenue is usually collected by the ISO or transmission owners.

It should be noted that congestion cost calculations vary depending on the market mechanism and ISO procedures. In this thesis, congestion costs will be obtained from the sum of uplift charges, system re-dispatch payments and congestion revenues together.

3.2.4 Congestion cost Illustrative Example

A simple 3-bus system connected to another network is under study of congestion costs calculation shown in figure 3.3. The market procedure will be applied as the following:

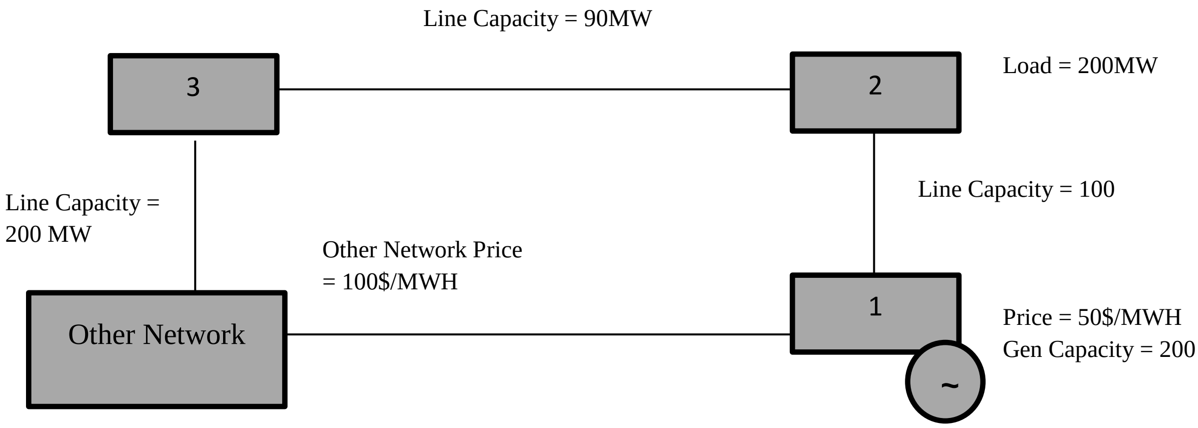


Figure 3.3 3-bus system of illustrative example

At Market Dispatch Stage:

MCP at generator bus (bus#1) is 50$/MWH, and the total energy cost to deliver 200MW is equal to:

50$/MWH X 200MW = **10,000$/hr**

At Congestion Re-Dispatch Stage:

Line 1-2 is maximum flow limit is considered (100MW). Thus, the rest of energy will be delivered through another path to the load bus (bus#2). The other path includes the other network through bus#3 to the load bus.

At bus#1: the power cost is 50$/MWH

At bus#2: the power cost is 100MW@50$/MWH from generator bus (bus#1) and remaining 100MW @100$/MWH from the other network resulted in:

(100$ + 50$)/2 = 75$/MWH

Thus, the total energy cost will be 75$/MWH X 200MW = **15,000$/hr**

The difference is 5,000$/hour is considered to be an **Uplift Charges**.

The second charge appears for the generator at bus#1. It was selected to sell 200MW of power at Market Dispatch stage. However the amount of power sold was reduced to 100MW at Market Re-Dispatch stage. Assuming a loss of 10% of profit for generator at bus#1 yields:

10% of (100MW @ 50$/MWH) = 500$/hr to be paid to generator at bus#1 as a lost profit. This is considered as a **System Re-Dispatch Payments**.

The third charge appears due to congestion on transmission line between bus#2 and bus#3. ISO defines the line capacity of power transfer to be 90MW. In congestion re-dispatch stage, the flow was equal to 100MW. This means that there was 10MW above the line limit. So:

100MW - 90MW = 10MW extra flow

Then, **Congestion Revenues** equals to the extra flow multiplied by the interface power price which is equal to:

10MW X 100#/MWH = 1000$/hr.

It can be concluded that in the previous scenario the total cost of energy was 15,000$/hr instead of 10,000$/hr due to the congestion. The congestion cost is 5,000$/hr will be divided to 500$/hr revenue to generation owners and 1000$/hr to transmission owners. The other 3500$/hr is due to the compensation from other network of 100MW @ 100$/MWH.

3.3 Mathematical Representation

A. Optimal Power Flow Equations (OPF)

The goal of optimal power flow is to minimize the costs of meeting load demand while maintaining the security of the system [23]. The objective function f(x) reflects the cost associated with generating power in the system. The quadratic cost model for generation of power is:

$$C_{pGi} = a_i + b_i P_{Gi} + c_i P_{Gi}^{\ 2} \qquad (3.4)$$

Where;

C_{pGi} = total generation cost

P_{Gi} = amount of generation in MW at generator i, and

a_i, b_i and c_i are constant of quadratic cost function.

The objective function for the entire power system can be written as the sum of the quadratic cost model at each generator [24]. That is:

$$f(x) = \sum_t (a_i + b_i P_{Gi} + c_i P_{Gi}^{\ 2}) \qquad (3.5)$$

Subjected to the constraints:

$$P_{imin} \leq P_i \leq P_{imax}$$

$$Q_{imin} \leq Q_i \leq Q_{imax}$$

$$V_{imin} \leq V_i \leq V_{imax}$$

$$\delta_{imin} \leq \delta_i \leq \delta_{imax}$$

For STATCOM:

$$Q_{smin} \leq Q_s \leq Q_{smax}$$

where:

f(x): the total reactive power loss in the network.

Q_s: the reactive power injected by the STATCOM into the system.

Q_{smin}: minimum limit of reactive power injected.

Q_{smax}: maximum limit of reactive power injected.

B. Congestion Cost Calculation

1. Market Clearing Price (MCP)

The MCPs are obtained through MATPOWER 4.1 based on optimal AC load flow (OPF) solver minimizing the total system generation cost and subjected to expanded limits in both generators and transmission network constraints.

2. Location Marginal Prices (LMP)

The LMPs are also obtained by MATPOWER 4.1 based on an optimal marked based AC load flow solver minimizing the total system generation cost and subjected to generators and transmission network constraints.

3. Uplift Charges

The uplift charges are included in the LMPs calculation. The LMPs are obtained from OPF and adjusted to network losses and they are out of merit generators costs as well.

4. **System Re-Dispatch Payments (SRP)**

SRP are obtained through the following equations:

$$SRP = \sum_{i=1}^{n} RP_i \quad (3.6)$$

$X_i = Y_i - Z_i$, Subjected to $X_i > 0$

(3.7)

$RP_i = X_i \times LMP_i \times PP_i$

(3.8)

Where;

n = Total number of generators.

i = Congested bus number.

RP_i = Re-Dispatch Payment for generator i.

LMP_i = Location Marginal Price at Bus i.

Y_i = Selected generation output at Market Dispatch stage for generator i.

Z_i = Selected generation output at Congestion Re-Dispatch stage for generator i.

X_i = Reduced generation output at Congestion Re-Dispatch stage with respect to generation output at Market Dispatch stage for generator i.

PP_i = percentage lost profit for generator i.

5. **Congestion Revenues**

The total Congestion Revenues (TCR) is obtained through the following equations:

$\mathrm{TCR} = \sum_{i=1}^{n} \mathrm{CR}_i$

(3.9)

$EF_i = TF_i - AF_i$

(3.10)

$CR_i = LMP_i \times EF_i$

(3.11)

Where;

n = Total number of buses.

i = Congested bus number.

CR_i = Congestion Revenues at bus i.

LMP_i = Location Marginal Price at bus i.

TF_i = Total power flow across bus i.

AF_i = Accepted safe power flow across bus i defined by ISO.

EF_i = Extra power flow across line i.

6. Revenue Rate (RR)

The RR refers to the rate for the STATCOM to cover its cost from savings in congestion costs. It is obtained by the following equations:

$TCS_i = TCB – TCC_i$

(3.12)

Where;

RR_i = Revenue Rate ($/hr) for equipment i,

TCS_i = Total saving in congestion costs ($/hr) after the addition of equipment i,

TCB = Total congestion costs ($/hr) for the base case,

TCC_i = Total congestion costs ($/hr) after the addition of equipment i.

7. **Payback Period**

The PP refers to the operating time required for STATCOM to cover its cost from saving in congestion costs. It is obtained by the following equations:

$$PP_i = \frac{\text{STATCOM Cost}}{RR_i} \tag{3.13}$$

Where;

PP_i = Payback period (hours) of equipment i.

Another approach is to calculate the annual cost of the STATCOM cost and compare it with the annual saving from congestion cost.

3.4 Solution Method: Genetic Algorithm (GA)

GA is general purpose optimization algorithm based on the mechanics of natural selection and genetics [25]. GA is global search technique based on the mechanism of natural selection and genetics. They can search several possible solutions simultaneously and produces high quality solutions. They operate on string structures (chromosomes) representing the control parameters (phenotype) of a given problem. Chromosomes themselves are composed of genes. The real value of a control parameter is called allele. [26]

The optimization technique works at the following way:

1. Parent selection:

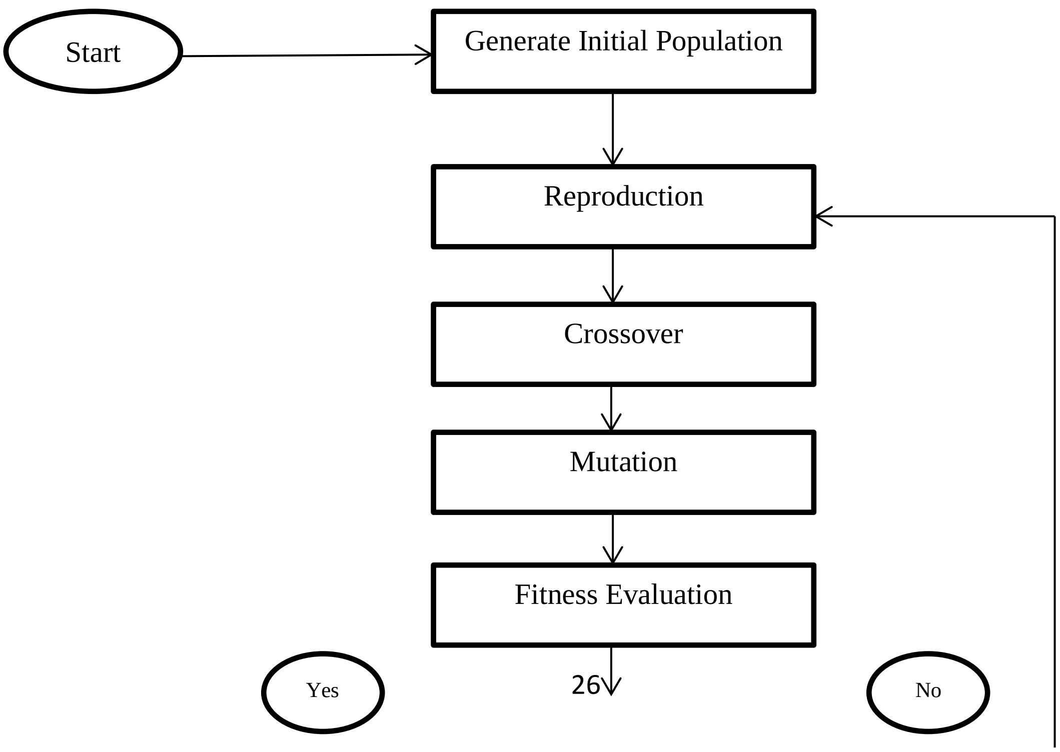
Where by two chromosomes are selected from the parent population based on their fitness value i.e. solutions with high fitness value have a high chance to pass to the next generation.

2. Crossover:

This operator is responsible for the structure of recombination and the convergence speed of the GA and is usually applied with high probability. Chromosomes of two parents selected are combined to form new chromosome that inherit segments of information stored in parent chromosomes.

3. **Mutation**:

This operator is responsible for the injection of new information. With a small probability, random genes of the offspring chromosomes are being replaced by new ones. This procedure will help to bring new characteristics that did not exist in the old population. Figure 3.4 shows a flow chart of GA algorithm.



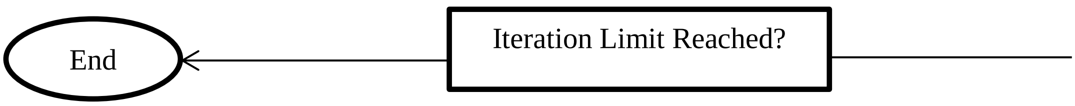


Figure 3.4 Genetic Algorithm Flowchart

In this thesis, GA is used to find the optimum allocation to install STATCOMs in the 16-Bus power system subjected to objective function of minimizing reactive power loss in power transmission network.

3.5 Solution Approach

A case study will be presented in this thesis. A 16-Bus 380KV real system will be under study. The initial analysis of Location Marginal Prices (LMPs) are obtained through a MATLAB based program called MATPOWER version 4.1. It is an open code and has powerful routines for solving and optimizing power system load flow equations called Optimal Power Flow (OPF).

After obtaining the base case MCPs and LMPs, contingency analysis with three scenarios is conducted that are:

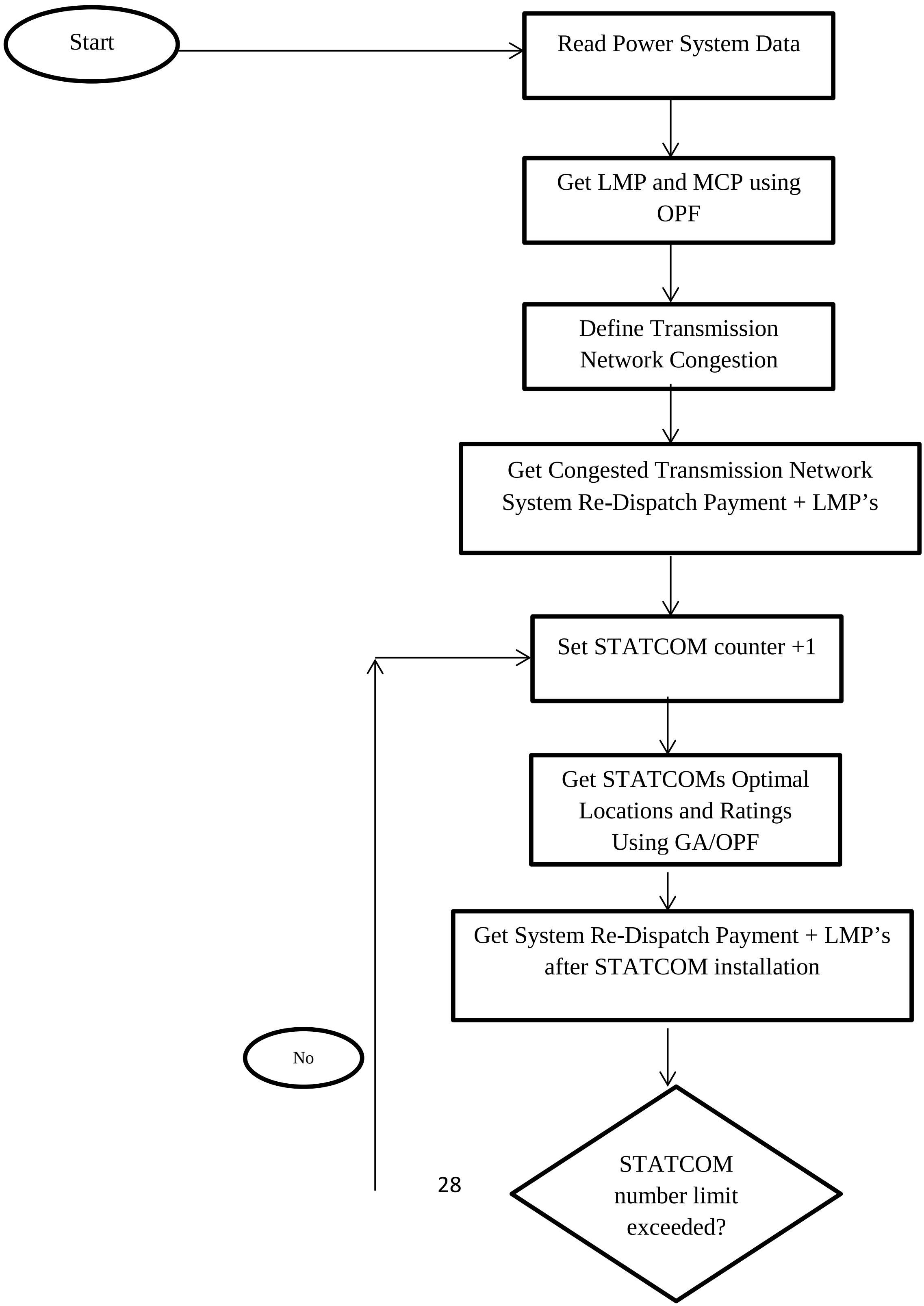
(A) Removal of most loaded line.

(B) Removal of two most loaded lines and,

(C) Reduction of the least cost generating unit capacity by 25%.

Congestion costs will be calculated for each case. After getting the initial congestion costs, installation of STATCOMs will be simulated in order to find the optimum location, rating and the number of STATCOMs for congestion removal and to enhance system security and reliability. The number of the required STATCOMs will be used by trial and error. Then, system dispatch payment and new

LMPs prices will be calculated again with the proposed locations of STATCOMs for each possible case. Finally, revenue rate will be calculated for the optimum locations for STATCOMs. Figure 3.5 shows the proposed solution for defining the optimum locations, ratings and the optimum number of STATCOMs to be installed in a congested transmission network .



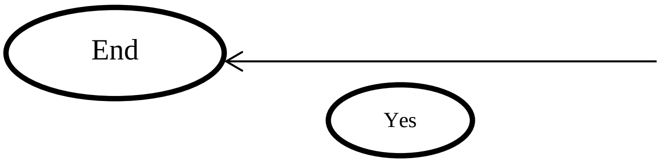


Figure 3.5 Methodology Flowchart

CHAPTER 4

4. SYSTEM STUDIES

4.1 Power System Under Study Description

The power system under study is a typical 16-bus 380KV Middle Eastern network. It consists of four (4) generation plants with a total capacity of 13,200 MW. It contains thirty six (36) transmission branches. The total load is 11,421 MW. Figure 4.1 shows the single line diagram of power system under study.

Generators data, bus data and transmission lines data are shown in Appendix A. Due to unavailability of exact generators coefficients cost data, the IEEE 30 bus system generator cost data are used.

The simulation of the power system and optimal power flow are implemented using MATLAB and MATPOWER 4.1

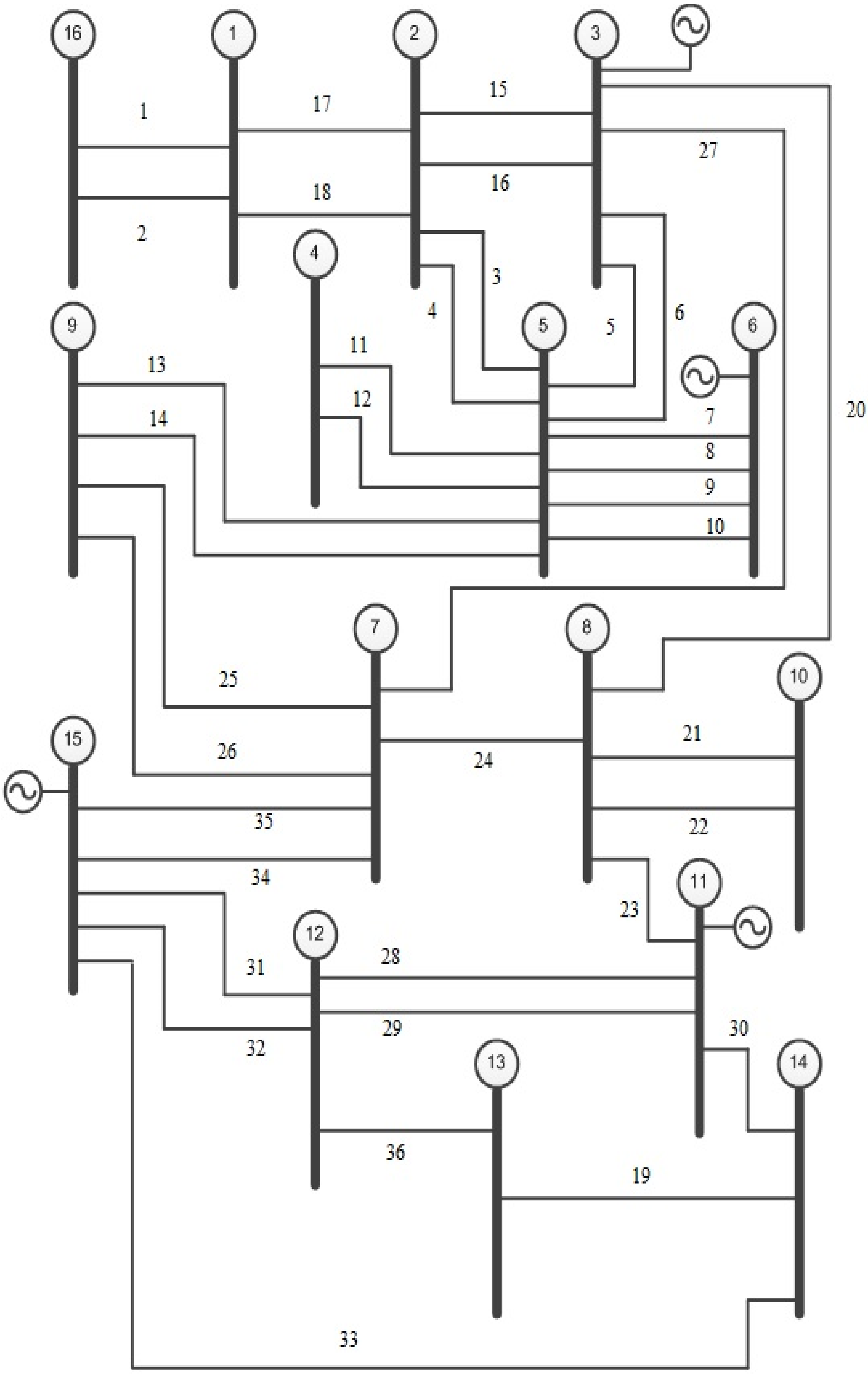


Figure 4.1 16-Bus 380 KV system under study

4.1.1 Base Case:

In order to obtain Market Clearing Price offered by generation companies with no transmission constraints, the following assumptions are made in the base case:

1. Generators output limits are considered [P_{max}, P_{min}].
2. Branch power flow is unlimited.
3. Power transmission losses are negligible.

The results of optimal power flow (OPF) to obtain bus data, branch flow, MCPs and LMPs for the base case are shown in table 4.1.

Table 4.1 Base Case OPF Results

Bus	Voltage		Generation		Load		λ
#	**Mag**	**Angle**	**P(MW)**	**Q(MVAR)**	**P(MW)**	**Q(MVAR)**	**($/MWH)**
1	1.025	-6.434	-	-	151	83	96.572
2	1.027	-5.774	-	-	2400	575	96.450
3	1.05	*0.0	2332.97	257.62	0	0	95.319
4	0.965	-1.306	-	-	35	205	109.290
5	1.037	-4.06	-	-	1600	500	96.127
6	1.05	-1.996	2686.37	814.35	0	0	95.773
7	1.026	-3.077	-	-	1140	415	95.952
8	1.028	-4.617	-	-	1155	375	96.232
9	1.028	-4.628	-	-	450	140	96.225
10	1.029	-11.759	-	-	550	107	97.538
11	1.05	-0.768	1891.88	545.64	0	0	95.594
12	1.025	-4.177	-	-	2030	297	96.241
13	0.997	-9.976	-	-	545	65	97.368
14	0.989	-9.207	-	-	1200	365	97.226
15	1.05	5.076	4600	770.84	0	0	94.558
16	1.024	-6.757	-	-	100	50	96.629

The results show a total generation of 11,511.22 MW and 2,388.28 MVAR, Total Load of 11,421 MW and 3,177 MVAR and an average LMPs of 97.068 $/MWH. The total cost of the base case is 527,308.78 $/hr.

Table 4.2 shows power flow across the transmission network ranked by most loaded lines. The flow shows that the maximum loaded branch is No. 34 that connects bus#15 and bus#7 with 955.188 MW flow. Table 4.3 states a power system summary of the base case.

Table 4.2 Power Flow Across the Network of Base Case

Branch #	From Bus	To Bus	From Bus Injection		To Bus Injection		Losses	
			MW	MVAR	MW	MVAR	MW	MVAR
34	15	7	995.188	160.68	-988.12	-65.98	7.065	144
35	15	7	995.188	160.68	-988.12	-65.98	7.065	144
31	15	12	940.80	130.60	-932.93	-47.05	7.866	153.75
33	15	14	843.55	207.59	-832.33	-101.05	11.222	219.32
32	15	12	825.29	111.30	-818.34	-43.86	6.944	134.87
3	5	2	758.08	200.48	-756.87	-188.86	1.206	24.47
4	5	2	758.08	200.48	-756.87	-188.86	1.206	24.47

Table 4.3 Base Case System Summary

No of Generators	4
No of Buses	16
No of committed Generators	4
No of Loads	12
No of Branches	36
Total Load	11,421 MW and 3,177 MVAR
Total Gen Capacity	13,800 **(MW)**, -4,652 to 6,474 **(MVAR)**
Actual Generation	11,511.2 MW and 2,388.3 MVAR
LMP Average	97.068 $/MWH (max 109.290, min 94.558)
Total Generation Cost (MCP)	527,308.78 $/hr

4.2 Defining Power Transmission Network Congestion

In order to define congestion zones, contingency analysis is done on the 16-bus system shown in figure 4.1. This is done through three different scenarios as the following:

Case A: Removal of most loaded line.

Case B: Removal of two most loaded lines.

Case C: Reduction of power production of the least cost generator.

These scenarios could occur in power transmission network due to forced outages for maintenance purposes on temporary basis.

Case A: Removal of Most Loaded Line.

The most loaded line in the base case was found to be branch# 34 as shown in table 4.2. When this branch was removed, OPF results for bus data and new LMPs are shown in table 4.4.

The results show a total generation of 11,524.2 MW and 2,716.9 MVAR. The new LMPs Average is 96.379 $/MWH. The total cost of power after re-dispatch is 528,665.19 $/hr (1,356.41$/hr increase compared to base case).

Generation re-dispatch prices had a slight change in generating units. Generation plant at bus#3 increased its production by 30 MW and generation plant at bus#6 increased by 37 MW. On the other hand, generation plant at bus#11 reduced its production by 54 MW.

One more observation is that the voltage profile of bus#13 and bus#14 has been reduced compared to the base case. This is caused by MVAR loss in the network. This could lead to a load rejection from the transmission network. It also could affect system stability. It is then required to note this deviation in voltage profile in the mentioned buses and resolve the problem.

Table 4.4 Bus and LMPs results for Case A

Bus	**Voltage**		**Generation**		**Load**		**λ**
#	**Mag**	**Angle**	**P(MW)**	**Q(MVAR)**	**P(MW)**	**Q(MVAR)**	**($/MWH)**
1	1.025	-6.465	-	-	151	83	97.889
2	1.027	-5.804	-	-	2400	575	97.762
3	1.05	*0.0	2363.15	348.82	0	0	96.526
4	0.964	-1.331	-	-	35	205	110.828
5	1.036	-4.093	-	-	1600	500	97.451
6	1.05	-2.0	2723.82	864.26	0	0	97.084
7	1.014	-3.597	-	-	1140	415	97.710
8	1.019	-4.477	-	-	1155	375	96.792
9	1.02	-4.985	-	-	450	140	97.884
10	1.02	-11.744	-	-	550	107	98.261
11	1.05	1.142	1837.22	695.37	0	0	92.861
12	1.021	-0.884	-	-	2030	297	91.291
13	0.993	-6.694	-	-	545	65	92.360
14	0.985	-5.899	-	-	1200	365	92.189
15	1.046	9.971	4600	808.44	0	0	87.236
16	1.024	-6.788	-	-	100	50	97.945

Power flow across the network is shown in table 4.5. The power that was carried by branch#34 has been distributed mostly along branch#35 and the rest of power is distributed on the rest of the transmission network branches.

The maximum power limit to be carried by a 380KV transmission line is 1,650MVA. Assuming the power factor will be 0.85 in the power system under study, the maximum MW capacity of a line is 1,400MW. As shown in table 4.5, after removing branch#35, an overloading situation occurred in branch#34 with 1,621.57 MW. This results in an increase in LMP with maximum rate at bus#4 with 110.828$/MWH and a minimum rate at bus#15 with 87.236$/MWH.

Moreover, a matter that would affect power transmission network is power losses in the overloaded transmission line. The MW loss in branch#34 increases to 19.046 MW comparing to the loss in branch#34 MW loss in base case which was 7.065 MW. Furthermore, reactive power loss in the same branch increased from 114 MVAR in the base case to 387.78 MVAR after removing branch#35.

Table 4.5 Branch Flow Results for Case A

Branch #	From Bus	To Bus	From Bus Injection		To bus Injection		Losses	
			MW	MVAR	MW	MVAR	MW	MVAR
34	15	7	1621.57	304.99	-1602.54	34.25	19.026	387.78
31	15	12	1092.92	148.86	-1082.25	-9.96	10.670	208.56
23	8	11	-995.19	-216.70	1000.15	288.51	4.961	105.46
32	15	12	958.73	127.29	-949.31	-11.26	9.419	182.94
33	15	14	926.78	227.30	-913.18	-73.48	13.593	265.66

Case B: Removal of Two (2) Most Loaded Lines.

As shown in table 4.2, branch#35 and branch#34 are the two most loaded lines in the base case.

To be able to determine the importance of the chosen lines to the system, other lines are used to be compared with the most loaded lines. That is to choose two different lines from the system to examine the effect on generation total cost and LMPs. Branch#7 and #8 are chosen to be removed from the system. The reason of choosing them is that they are connected to generation bus#6 and the deliver power to a large number of buses with a minimum rout of power transmission. OPF results and branch flow results are shown in table 4.6 and 4.7 respectively.

The results show a total generation of 11517.39 MW and 2553.34 MVAR. The total cost is 527898.02$/hr and LMPs average is 97.2965.

Table 4.6 Bus and LMPs Results for Case B (branches #7 and #8)

Bus	Voltage		Generation		Load		λ
#	**Mag**	**Angle**	**P(MW)**	**Q(MVAR)**	**P(MW)**	**Q(MVAR)**	**($/MWH)**
1	1.017	-6.491	-	-	151	83	96.834
2	1.019	-5.820	-	-	2400	575	96.706
3	1.05	0	2338.49	441.91	0	0	95.540
4	0.954	-1.211	-	-	35	205	109.982
5	1.027	-4.077	-	-	1600	500	96.179
6	1.05	0.093	2682.64	760.86	0	0	95.642
7	1.024	-3.074	-	-	1140	415	96.179
8	1.027	-4.612	-	-	1155	375	96.459
9	1.023	-4.641	-	-	450	140	96.462
10	1.028	-11.771	-	-	550	107	97.777
11	1.05	-0.743	1896.26	556.58	0	0	95.813
12	1.025	-4.157	-	-	2030	297	96.462
13	0.977	-9.956	-	-	545	65	97.591
14	0.989	-9.186	-	-	1200	365	97.449
15	1.05	5.092	4600	793.98	0	0	94.775
16	1.016	-6.819	-	-	100	50	96.894

Table 4.7 Branch flow Results for Case B (branches #7 and #8)

Branch #	From Bus	To Bus	From Bus Injection		To bus Injection		Losses	
			MW	**MVAR**	**MW**	**MVAR**	**MW**	**MVAR**
9	5	6	-1336.19	-294.39	1341.32	380.43	5.133	104.96
10	5	6	-1336.19	-294.39	1341.32	380.43	5.133	104.96
34	15	7	995.70	172.34	-988.59	-76.97	7.103	144.78
35	15	7	995.70	172.34	-988.59	-76.97	7.103	144.78

It is clear that branches #34 and #35 removal has the most significant effect on the system due to the large amount of power carried by them. Also, they are carrying power from the least cost generation bus#15. This lead to take all possible power can be generated to be delivered to the system. Thus, removing branches connected to more expensive generation bus would not affect the generation cost and the LMPs. A summary of the comparison between removing the two sets is shown in table 4.8.

Table 4.8 Summary of the comparison between the effects of removing two set of branches

Branches Removed	**Comparison Between Line Set Removal**					
	Generation		**Losses**		**Cost Diff w.r.t Base Case**	**LMP's**
	MW	**MVAR**	**MW**	**MVAR**	**$/hr**	**$/MWH**
7 and 8	11517.39	2553.34	96.393	1606.95	589.24	97.2965
34 and 35	11553.72	3409.44	132.722	2322.86	31107.49	104.207

OPF, MCBs and LMPs results after removing branch#34 and #35 are shown in table 4.9.

Results show a total generation of 11,553.72 MW and 3,409.44 MVAR and total Load of 11,421 MW and 3,177 MVAR. The total cost is 558,416.27$/hr (an increase of 31,107.49$/hr compared to the base case). New LMPs average is 104.207.

Beside the large increase of total LMPs, system stability and reliability are in major risk done to the following:

For generation unit at bus#3, the generation increases to 2,826.78 MW and in re-dispatch stage with 493.81 MW increase in generation. For generation unit at bus#6, an increase of power generation of 565.21 MW is observed.

On the other hand, generation unit at bus#11 resulted in a decrease in power generation of 441.3 MW. Finally, generation unit at bus#15 resulted in a decrease in power generation of 575.24 MW that would be compensated for due in the market re-dispatch stage.

The major concern in this case that the results for bus voltages show a large decrease in voltage profile of bus#13 with a magnitude of 0.958 p.u. The system security and reliability in this case may be compromised and this issue should be resolved.

Table 4.9 Bus and LMPs Results for Case B (branches #34 and #35)

Bus	**Voltage**		**Generation**		**Load**		**λ**
#	**Mag**	**Angle**	**P(MW)**	**Q(MVAR)**	**P(MW)**	**Q(MVAR)**	**($/MWH)**
1	1.023	-6.320	-	-	151	83	116.636
2	1.025	-5.656	-	-	2400	575	116.484
3	1.05	*0.0	2826.78	662.82	0	0	115.071
4	0.962	-1.118	-	-	35	205	132.147
5	1.034	-3.904	-	-	1600	500	116.089
6	1.05	-1.4	3251.6	1013.02	0	0	115.556
7	0.984	-8.761	-	-	1140	415	117.683
8	0.984	-7.549	-	-	1155	375	117.382
9	0.999	-8.145	-	-	450	140	117.367
10	0.981	-15.361	-	-	550	107	120.257
11	1.005	2.473	1450.58	503.58	0	0	73.529
12	0.989	4.409	-	-	2030	297	73.242
13	0.958	-1.698	-	-	545	65	74.465
14	0.950	-0.79	-	-	1200	365	74.318
15	1.049	19.962	4024.76	1230	0	0	70.383
16	1.022	-6.644	-	-	100	50	116.707

Table 4.10 shows branch flow across the network results for Case B. After removing branch#35 and branch#34 together, an overloading situation occurred in branch#23 and branch#31 with 1,631.81 MW and 1,521.64 MW respectively. This will result in an increase in major uplift charges. An increase of MW loss in branch#33 is 22.986 MW comparing to the base case which was 11.222 MW. Furthermore, reactive power loss, in the same branch, increased from 219.32 MVAR in the base case to 449.24 MVAR after removing branch#34 and #35.

Table 4.10 Branch Flow Across the Network Results for Case B

Branch #	From Bus	To Bus	From Bus Injection		To bus Injection		Losses	
			MW	MVAR	MW	MVAR	MW	MVAR
23	8	11	-1618.29	11.90	1631.81	244.35	13.517	287.37
31	15	12	1521.64	430.08	-1499.77	-70.41	21.865	427.41
32	15	12	1334.87	373.82	-1315.57	-63.98	19.303	374.9
33	15	14	1168.25	426.1	-1145.27	-85.4	22.986	449.24

Case C: Reduction of power production of the least Cost generator.

It is not practical to take a whole power plant for an outage. In real life, electric power plant consists of several generating units. Some units could be removed for maintenance purposes. In this particular case, the cheapest generation plant was chosen to reduce 25% of its maximum production capacity. Table 4.11 shows generation data for power system under study. The least cost generation plant is the one at bus#15 with a cost of 0.00834$/MWH.

Table 4.11 Generation Data in Power System under Study

Bus#	PG	PQ	Qmax	Qmin	Vg	Mbase	Status	Pmax	Cost ($/MW)
3	3000	642	1312	-1096	1.015	100	1	3000	0.02
6	3500	405.5	2620	-1590	1.045	100	1	3500	0.0175
11	2700	704.8	1312	-1096	1.03	100	1	2700	0.025
15	4700	405.5	1230	-870	1.03	100	1	3500	0.00834

OPF results, MCBs and LMPs of case C are shown in table 4.12.

The results show a total generation of 11505.43 MW and 11421 MVAR. The total power cost is 560928.16 $/hr (an increase of 33619.38$/hr compared to the base case).

A major economical change has occurred in LMPs prices with an average of 112.125$/MWH. This is understandable because the forced outage of the cheapest generation plant at bus#3 is equal to 875 MW. This led to the selection of more expensive ones to compensate the same amount of power that was reduced. The compensation was 358.81MW, 408.75 and 301.83 from generators at bus#3, 6 and 11 respectively.

Table 4.12 Bus and LMPs Results for Case C

Bus	**Voltage**		**Generation**		**Load**		**λ**
#	**Mag**	**Angle**	**P(MW)**	**Q(MVAR)**	**P(MW)**	**Q(MVAR)**	**($/MWH)**
1	1.025	-6.223	-	-	151	83	111.066
2	1.027	-5.562	-	-	2400	575	110.926
3	1.05	*0.0	2691.6	265.12	0	0	109.664
4	0.965	-1.045	-	-	35	205	125.692
5	1.037	-3.8	-	-	1600	500	110.548
6	1.05	-1.417	3095.12	820.5	0	0	110.079
7	1.028	-6.486	-	-	1140	415	111.114
8	1.028	-7.637	-	-	1155	375	111.366
9	1.029	-6.661	-	-	450	140	111.139
10	1.03	-14.769	-	-	550	107	112.870
11	1.05	-4.167	2193.71	534.87	0	0	110.686
12	1.026	-8.972	-	-	2030	297	111.729
13	0.998	-14.798	-	-	545	65	113.031
14	0.99	-14.049	-	-	1200	365	112.867
15	1.05	-1.245	3525	637.42	0	0	110.090
16	1.024	-6.546	-	-	100	50	111.133

Power flow across the network is shown in table 4.13. The results show no system security issue regarding overloading or voltage decrease to be considered.

Table 4.13 Branch Flow Results for Case C

Branch #	From Bus	To Bus	From Bus Injection		To Bus Injection		Losses	
			MW	**MVAR**	**MW**	**MVAR**	**MW**	**MVAR**
31	15	12	787.76	109.91	-782.23	-72.07	5.531	108.11
3	5	2	778.6	198.08	-777.34	-185.24	1.266	26.69
7	5	6	-772.08	-189.53	773.78	205.13	1.696	34.69

Case D: Global Contingency (Case B and C).

In this case, both case B and case C are considered together as a global contingency. It is a simulation of a worst case scenario that could occur in the system. OPF, MCBs and LMPs results are shown in table 4.14.

Results show a total generation of 11,537.73 MW and 3,084.09 MVAR and total Load of 111,421 MW and 3,177 MVAR. The total cost is 566,830.64$/hr (an increase of 39,521.86$/hr compared to the base case). New LMPs average is 112.7605$/MWH.

Beside the significant increase of total LMPs, system stability and reliability are in major risk done to the following:

For generation unit at bus#3, the generation increases to 2,829.32 MW and in re-dispatch stage with 496.35 MW increase in generation. For generation unit at bus#6, an increase of power generation of 567.42 MW is observed. Generation unit at bus#11 resulted in an increase in power generation of 37.75 MW

On the other hand, generation unit at bus#15 resulted in a decrease in power generation of 1075 MW that would be compensated for due in the market re-dispatch stage due to the 25 percent decrease.

The major concern in this case that the results for bus voltages show a large decrease in voltage profile of bus#13 with a magnitude of 0.969 p.u. The system security and reliability in this case may be compromised and this issue should be resolved.

Table 4.14 Bus and LMPs Results for Case D

Bus	**Voltage**		**Generation**		**Load**		**λ**
#	**Mag**	**Angle**	**P(MW)**	**Q(MVAR)**	**P(MW)**	**Q(MVAR)**	**($/MWH)**
1	1.023	-6.315	-	-	151	83	116.706
2	1.025	-5.652	-	-	2400	575	116.556
3	1.05	*0.0	2829.32	628.32	0	0	115.173
4	0.962	-1.116	-	-	35	205	132.208
5	1.034	-3.90	-	-	1600	500	116.160
6	1.05	-1.393	3253.79	999.29	0	0	115.663
7	0.987	-8.761	-	-	1140	415	117.512
8	0.989	-7.567	-	-	1155	375	117.244
9	1.002	-8.142	-	-	450	140	117.275
10	0.986	-15.305	-	-	550	107	119.574
11	1.013	2.286	1929.63	477.08	0	0	97.481
12	0.999	2.223	-	-	2030	297	97.499
13	0.969	-3.801	-	-	545	65	98.748
14	0.961	-2.939	-	-	1200	365	98.589
15	1.05	15.493	3525	979.40	0	0	95.003
16	1.022	-6.640	-	-	100	50	116.777

Table 4.15 shows branch flow across the network results for Case D. After removing branch#35 and branch#34 together, an overloading situation occurred in branch#23 and branch#31 with 1,613.25 MW and 1,315.86 MW respectively. This will result in an increase in major uplift charges. An increase of MW loss in branch#33 is 18.413 MW comparing to the base case which was 11.222 MW. Furthermore, reactive power loss, in the same branch, increased from 219.32 MVAR in the base case to 359.88 MVAR after removing branch #34 and #35.

Table 4.15 Branch Flow Across the Network Results for Case D

Branch #	**From Bus**	**To Bus**	**From Bus Injection**		**To bus Injection**		**Losses**	
			MW	**MVAR**	**MW**	**MVAR**	**MW**	**MVAR**
23	8	11	-1613.25	-25.72	1626.56	277.12	13.307	282.91
31	15	12	1315.86	334.29	-1299.76	-88.04	16.101	314.73
32	15	12	1154.34	289.85	-1140.12	-79.56	14.214	276.07
33	15	14	1054.81	355.27	-1036.39	-105.23	18.413	359.88

Table 4.16 shows a summary of the results of the base case and the three different scenarios.

Table 4.16 Summary of Base Case and Contingency Results

Case Profile	Gen Cost ($/hr) w.r.t Base Case	LMP's ($/MWH)	MW Losses	MVAR Losses
Base Case	0	97.068	90.2	1,493.57
Case A	+1,356.41	96.379	103.197	1,755.61
Case B	+3,1107.49	104.2073	132.722	2,322.86
Case C	+3,3619.38	112.125	84.426	1,365.33
Case D	+39521.68	112.760	111.421	3177

It can be noticed that in case D the LMP average is slightly more than case C. This can be explained due to the generation reduction at bus#15 and branch# 34 and #35 are actually carrying power from the same plant. Thus, the total generation from bus#15 will not be affected by the outage of the branches connected to it.

CHAPTER 6

5. APPLICATION OF STATCOM FOR CONGESTION ELIMINATION

5.1 Defining Congestion Elimination Mechanism

Independent System Operator (ISO) is responsible to resolve any possible congestion such that system security and reliability are not in risk. From the mentioned contingency analysis results in section 4.2, a solution of system security should be found and to maintain economic stability based on transactions made for electric power exchange in the MCP stage.

The solution based on power system expansion should have the following properties:

1. Enhance power system security and reliability that could be in risk due to power exchange.
2. Maintain Location Marginal Prices with the minimum deviation in case of congestion.
3. Reduce Generation total cost.
4. Attract investors to the electric power transmission market by defining economic revenues to them.

The major problem occurred on the contingency analysis in section 4.2 are found to be:

1. Overloading of transmission network branches which resulted in uplift charges and re-dispatch stage that affected LMPs.
2. Voltage profile decrement that would significantly affect power system stability and security.
3. Major increase in LMPs due to generation reduction of lest cost generation plant.

The proposed solution is to install a number of STATCOMs in the system under study to obtain the mentioned goals. The optimal location and ratings of STATCOMs in the transmission network are required in order to get the optimum operation conditions of the system subjected to all generation and transmission constraints. The objective function on which, the optimal solution is found, is to minimize reactive power loss in transmission network.

5.1.1 STATCOM Installation for Case A

The results showed that the optimum solution which resolves all problems is to install four STATCOMs in the system. Table 5.1 shows the results. The table shows different aspects of system results.

The generation column shows the total power generation produced. As the number of STATCOMs increases, the total generation is reduced due to the compensation of STATCOMs. The major effect of STSTCOMs installation can be noticed in MVAR generation reduction of 899.81 MVAR in the optimum solution.

Total active and reactive power losses are shown in the second column of the table. The optimal solution resulted in 92.745 MW loss and 1,687.16 MVAR. The installation of STATCOMs resulted in reducing both real and reactive power losses.

The last two columns explain economical effects after STATCOM installation. Total congestion costs resulted from generation re-dispatch, uplift charges are reduced after the installation of STATCOMs. The optimum solution resulted in LMPs average of 96.333 and a total cost reduction of 79.76% compared to the no STATCOM installation.

Table 5.1 Table 5.1 Results of System Data After Installing Different Number of STATCOMs For Case A

Number of Installed STATCOMs	**Most Loaded Line Removal (Case A)**					
	Generation		**Losses**		**Cost Diff w.r.t No STATCOM**	**LMP's**
	MW	**MVAR**	**MW**	**MVAR**	**$/hr**	**$/MWH**
1	11522.61	2473.6	101.613	1724.61	165.49	96.406
2	11521.70	2274.85	100.7	1707.27	296.13	96.579
3	11520.94	2031.09	99.942	1692.76	394.24	96.719
4	11513.75	1817.09	92.754	1687.16	1081.93	96.333
5	11512.01	1838.16	91.006	1684.9	1258.46	96.48831
6	11512.12	1227.16	91.115	1665.82	1283.72	96.86475
7	11512.12	1227.16	91.115	1665.82	1269.95	96.85575

Figure 5.1 shows total savings compared to the base case prices after installing different number of STATCOMs in the system. It shows that there are major improvement after installing the fourth STATCOM has a large deviation resulted in reducing the total cost from 394.24$/hr to 1081.93$/hr. On the other hand, after installing more than four STATCOMs, no improvement in cost saving is observed .

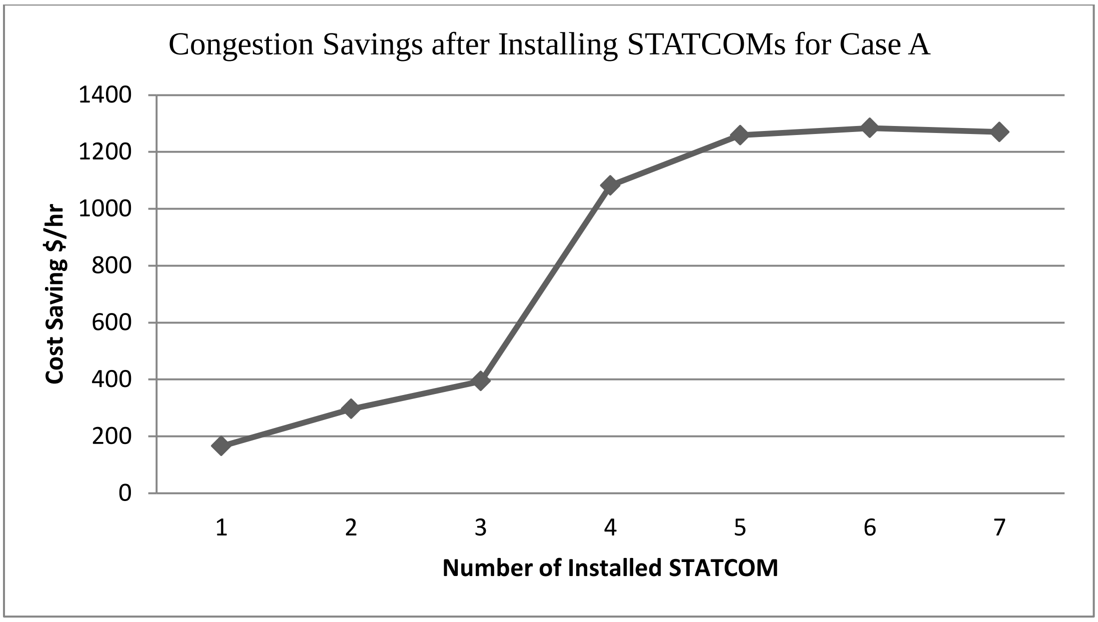


Figure 5.1 Total Savings w.r.t Base Case After Installing STATCOMs For Case A

The objective function of installing four STATCOMs in the system is shown in figure 5.2 and shows a success in finding the optimum locations and ratings of the four STATCOMs with minimizing reactive power loss in the transmission network. The results suggested that the four optimum locations of the proposed STATCOMs are bus# 4,8,13 and 14. Results are shown in table 4.13

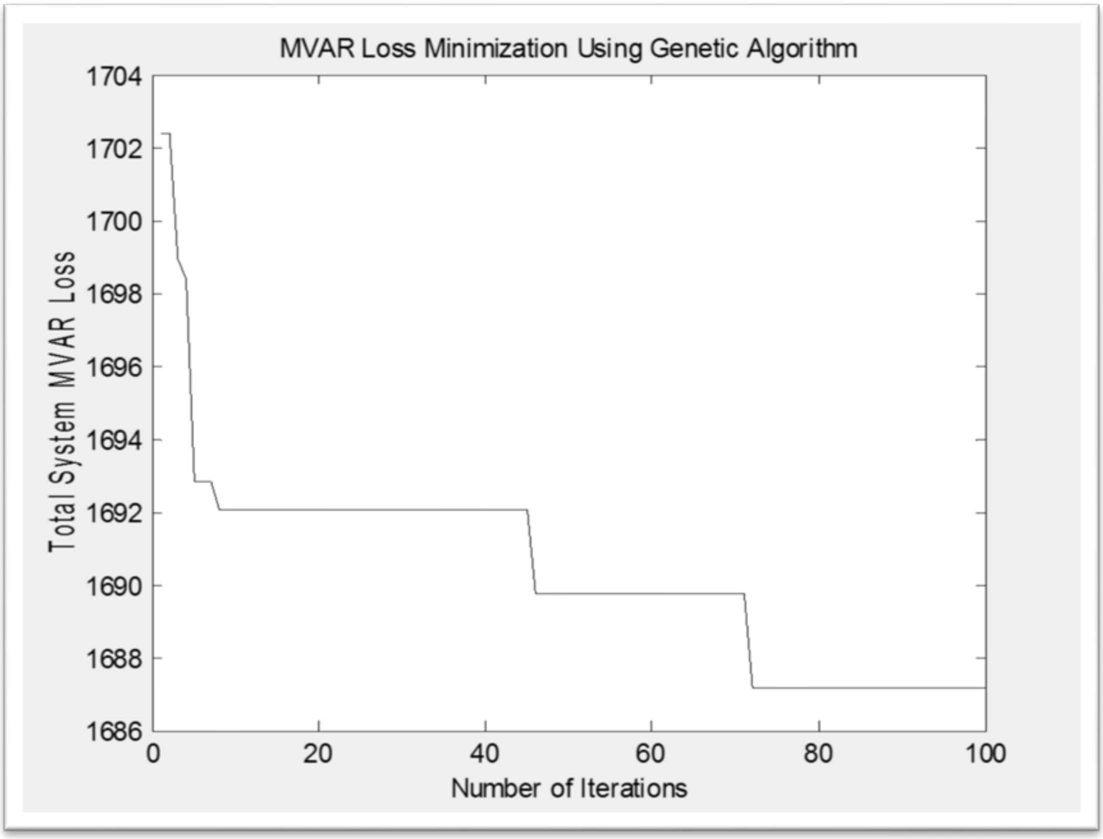


Figure 5.2 Optimization Results for Reactive Power Minimization of Case A

Table 5.2 Optimum Locations and Ratings of STATCOMs for Case A

Bus#	**STATCOM Rating (MVAR)**	**Corresponding MVAR Loss**
4	180.1050	1687.2
8	181.3546	
13	194.1849	
14	194.5337	

The difference made by STATCOMs placement in transmission network is 68.4 MVAR. Bus results are shown in table 5.3.

The results show a total generation of 11,513.75 MW and 1,817.09 MVAR. The new total power cost is 527,583.26 $/hr with a decrease of 1,081.93 $/hr (0.2%) in comparison with the case without STATCOMs.

The voltage profile of all buses is enhanced and stable compared to the case of no STATCOM.

Table 5.3 Bus and LMPs Results After Installing Four STATCOMS for Case A

Bus	**Voltage**		**Generation**		**Load**		**λ**
#	**Mag**	**Angle**	**P(MW)**	**Q(MVAR)**	**P(MW)**	**Q(MVAR)**	**($/MWH)**
1	1.027	-6.456	-	-	151	83	97.192
2	1.029	-5.797	-	-	2400	575	97.072
3	1.05	*0.0	2347	235.83	0	0	95.904
4	0.996	-6.534	-	-	35	205	105.578
5	1.039	-4.095	-	-	1600	500	96.761
6	1.05	-2.016	2704.55	688.6	0	0	96.409
7	1.021	-3.494	-	-	1140	415	96.822
8	1.029	-4.337	-	-	1155	375	96.458
9	1.026	-4.908	-	-	450	140	97.015
10	1.031	-11.456	-	-	550	107	97.807
11	1.05	1.382	1861.6	324.26	0	0	94.08
12	1.032	-0.684	-	-	2030	297	93.535
13	1.044	-6.178	-	-	545	65	94.479
14	1.031	-5.4	-	-	1200	365	94.333
15	1.05	9.965	4600	568.40	0	0	90.648
16	1.026	-6.778	-	-	100	50	97.249

Table 5.4 shows a branch flow across the network results. The results show a clear improvement in voltage profiles. The result of branch flow of the system after

installing STATCOMs in their optimal location showed an overload in branch#34 with 1,625.74 MW transmission along the line.

Table 5.4 Branch Flow Across the Network After Installing STATCOMs for Case A

Branch #	**From Bus**	**To Bus**	**From Bus Injection**		**To Bus Injection**		**Losses**	
			MW	**MVAR**	**MW**	**MVAR**	**MW**	**MVAR**
34	15	7	1625.74	281.88	-1606.87	53.63	18.87	384.6
31	15	12	1085.78	110.34	-1075.44	21.18	10.343	202.17
23	8	11	-1017.9	-118.95	1022.84	189.99	4.94	105.02
32	15	12	952.45	93.48	-943.32	16	9.131	177.34

5.1.2 STATCOM Installation for Case B

The results showed that the optimum solution which resolves all problems is to install four STATCOMs in the system. Table 5.5 shows the results. The table shows different aspects of system results.

The generation column shows the total power generation produced. As the number of STATCOMs increase, total generation is reduced due to the compensation of STATCOMs. The major effect of STSTCOMs installation can be noticed in the MVAR reducing generation of 852.8 MVAR in the optimum solution.

Total active and reactive power losses are shown in the second column of the table. The optimal solution resulted in 172.804 MW loss and 2,229.16 MVAR. The installation of STATCOMs resulted in reducing both real and reactive power losses.

The last two columns explain economical effects after STATCOM installation. Total congestion cost resulted from generation re-dispatch, uplift charges is reduced after the installation of STATCOMs. The optimum solution resulted in LMPs average of 103.7161 and a total cost reduction of 83.96% compared to no STATCOM installation.

Table 5.5 Results of System Data After Installing Different Number of STATCOMs

Number of Installed STATCOMs	Removal Of Two Most Loaded Line (Case B)					
	Generation		Losses		Cost Diff w.r.t No STATCOM	LMP's
	MW	MVAR	MW	MVAR	$/hr	$/MWH
1	11552.74	3178.05	131.742	2305.07	564.32	103.9409
2	11550.94	2927.07	129.945	2271.03	990.16	103.7523
3	11550.07	2781.05	129.074	2253.71	1031	103.7366
4	11548.8	2556.64	127.804	2229.16	1138.93	103.7161
5	11548.07	2400.98	127.069	2216.07	1226.7	103.7028
6	11547.08	2242.04	126.081	2196.68	1292.77	103.6896
7	11546.82	2095.26	125.816	2192.39	1300.13	103.6914

Figure 5.3 shows total savings compared to the base case price after installing different number of STATCOMs in the system. It shows that the major improved after installing the fourth STATCOM has resulted in reducing the total cost from 1,031$/hr to 1138.93$/hr. on the other hand, after installing more than four STATCOMs, the reduction has a slight deviation

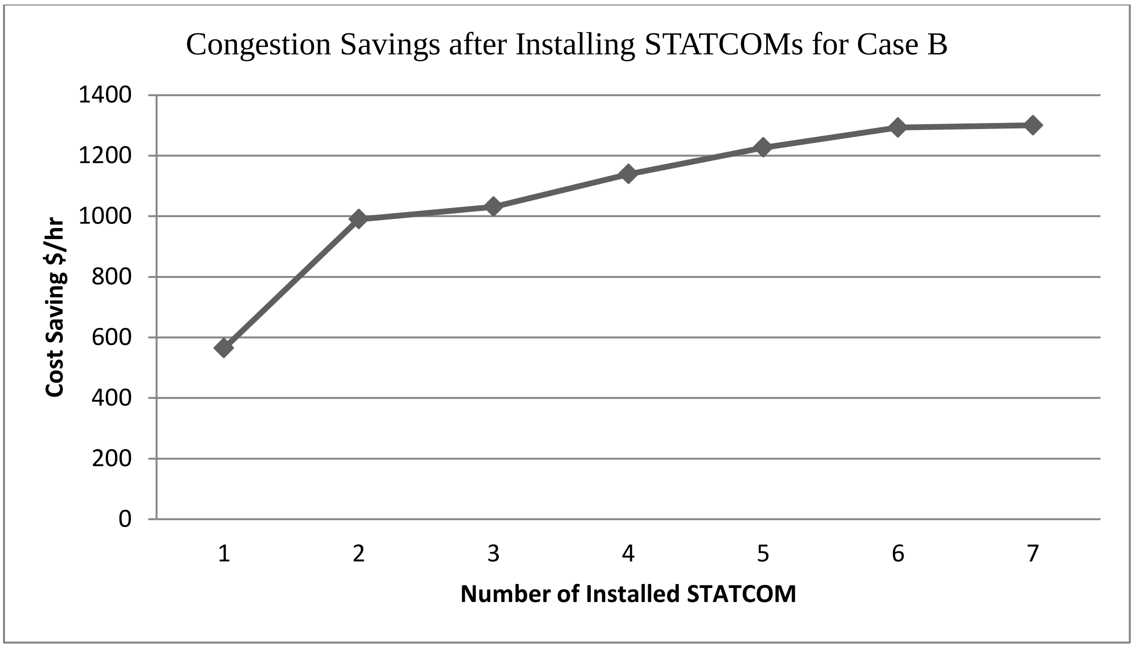


Figure 5.3 Total Savings w.r.t Base Case After Installing STATCOMs for Case B

The results of the objective function is shown in figure 5.4 and shows a success in finding the optimum location and rating of the four STATCOMs with minimizing reactive power loss in the transmission network. The results suggested that the four locations of the proposed STATCOMs are at bus# 8, 10, 12 and 14. Results are shown in table 5.6

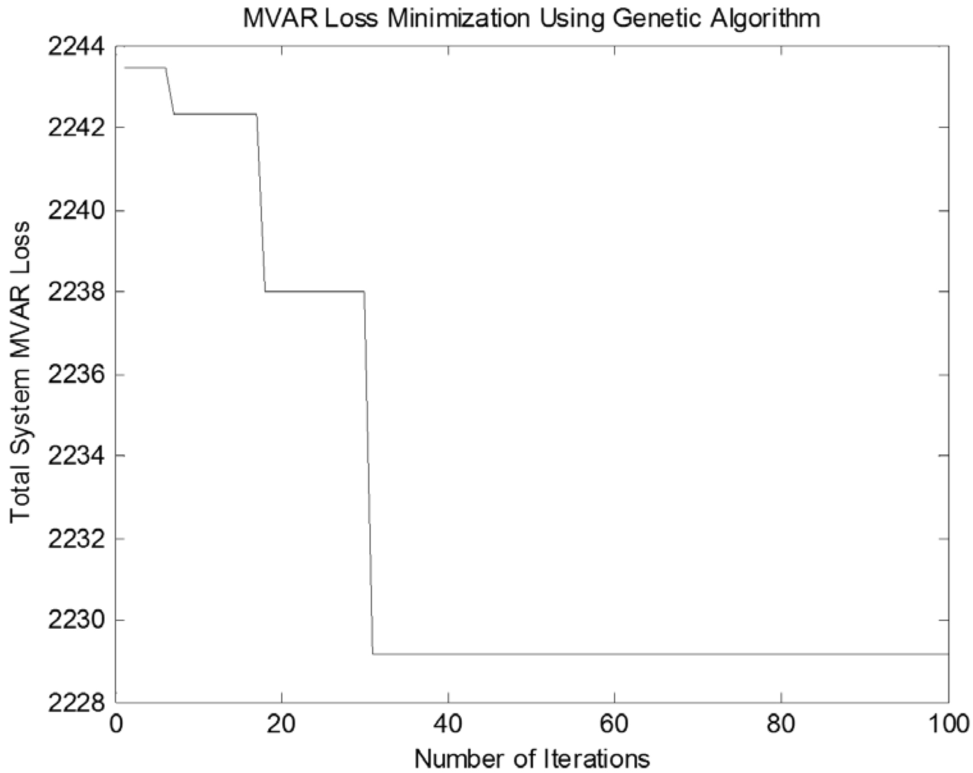


Figure 5.4 Optimization Results for Reactive Power Minimization for Case B

Table 5.6 Optimum Locations and Ratings of STATCOMs for Case B

Bus#	**STATCOM Rating (MVAR)**	**Corresponding MVAR Loss**
8	197.9684	2229.2
10	138.0400	
12	199.6548	
14	143.2863	

The difference made by STATCOMs placement is 93.7 MVAR. Bus results are shown in table 5.7. The results show a total generation of 11,548.8 MW and 2,556.64 MVAR. The new total power cost is 557,277.34 \$/hr with a decrease of 1,138.93 \$/hr (0.2%) in comparison with the case without STATCOMs.

It is clear that there is a major change of voltage profile of buses bus#13 and bus#14. This would be a success in preserving system security in the case of such contingency.

Table 5.7 Bus and LMPs Results After Installing STATCOMS For Case B

Bus	**Voltage**		**Generation**		**Load**		**λ**
#	**Mag**	**Angle**	**P(MW)**	**Q(MVAR)**	**P(MW)**	**Q(MVAR)**	**($/MWH)**
1	10.24	-6.308	-	-	151	83	116.283
2	1.026	-5.646	-	-	2400	575	116.134
3	1.05	*0.0	2819.15	451.06	0	0	114.766
4	0.963	-1.123	-	-	100	205	131.679
5	1.035	-3.896	-	-	1600	500	115.740
6	1.05	-1.399	3241.95	927.87	0	0	115.218
7	1.005	-8.585	-	-	1140	415	116.973
8	1.012	-7.414	-	-	1155	375	116.720
9	1.013	-8.023	-	-	450	140	116.776
10	1.049	-14.636	-	-	550	107	118.646
11	1.017	2.344	1443.04	237.86	0	0	73.152
12	1.008	4.277	-	-	2030	297	72.875
13	0.984	-1.549	-	-	545	65	73.772
14	0.979	-0.688	-	-	1200	365	73.656
15	1.05	19.636	4044.66	939.86	0	0	70.715
16	1.023	-6.632	-	-	100	50	116.353

The results of branch flow of the system after installing STATCOMs in their optimal location show an overload in branch#23 with 1,646.88 MW along the line as shown in table 5.8.

Table 5.8 Branch flow Across the Network After Installing STATCOMs for Case B

Branch #	From Bus	To Bus	From Bus Injection		To Bus Injection		Losses	
			MW	MVAR	MW	MVAR	MW	MVAR
23	8	11	-1633.72	146.17	1646.88	101.38	13.166	279.91
31	15	12	1528.04	327.53	-1506.79	18.96	21.258	415.53
32	15	12	1340.46	283.86	-1321.69	14.31	18.767	364.49
33	15	14	1176.16	328.47	-1154.17	-10.50	21.985	429.68

5.1.3 STATCOM Installation for Case C

The results showed that the optimum solution which resolves all problems is to install four STATCOMs in the system. Table 5.9 shows the results. The table shows different aspects of system results.

The generation column shows the total power generation produced. As the number of STATCOMs increase, total generation is reduced due to the compensation of STATCOMs. The major effect of STSTCOMs installation can be noticed in MVAR generation reduction of 552.64 MVAR in the optimum solution.

The total active and reactive power losses are shown in the second column of the table. The optimal solution resulted in 74.664 MW loss and 1,316.02 MVAR. The installation of STATCOMs resulted in reducing both real and reactive power losses.

The last two columns explain the economical effects after STATCOM installation. Total congestion cost resulted from generation re-dispatch, uplift charges is reduced after the installation of STATCOMs. As a result, STATCOM installation results in cost savings. The optimum solution results in LMPs average of 111.65 and a total cost reduction of 79.21% compared to no STATCOM installation.

Table 5.9 Results of System Data After Installing Different Number of STATCOMs For Case C

Number of Installed STATCOMs	Least Cost Generation Reduction (Case C)					
	Generation		Losses		Cost Diff w.r.t Base Case	LMP's
	MW	MVAR	MW	MVAR	$/hr	$/MWH
1	11504.13	2016.65	83.132	1339.91	142.6	112.0931
2	11503.6	1815.38	82.601	1329.58	201.04	112.0746
3	11503.13	1555.54	82.129	1320.53	253.11	112.061
4	11495.66	1464.01	74.664	1316.02	1074.43	111.65
5	11495.8	1274.07	74.802	1312.05	1059.235	111.02
6	11502.40	1169.18	81.403	1307.57	1189.48	110.981
7	11502.27	1096.32	81.267	1307.05	1348.01	110.347

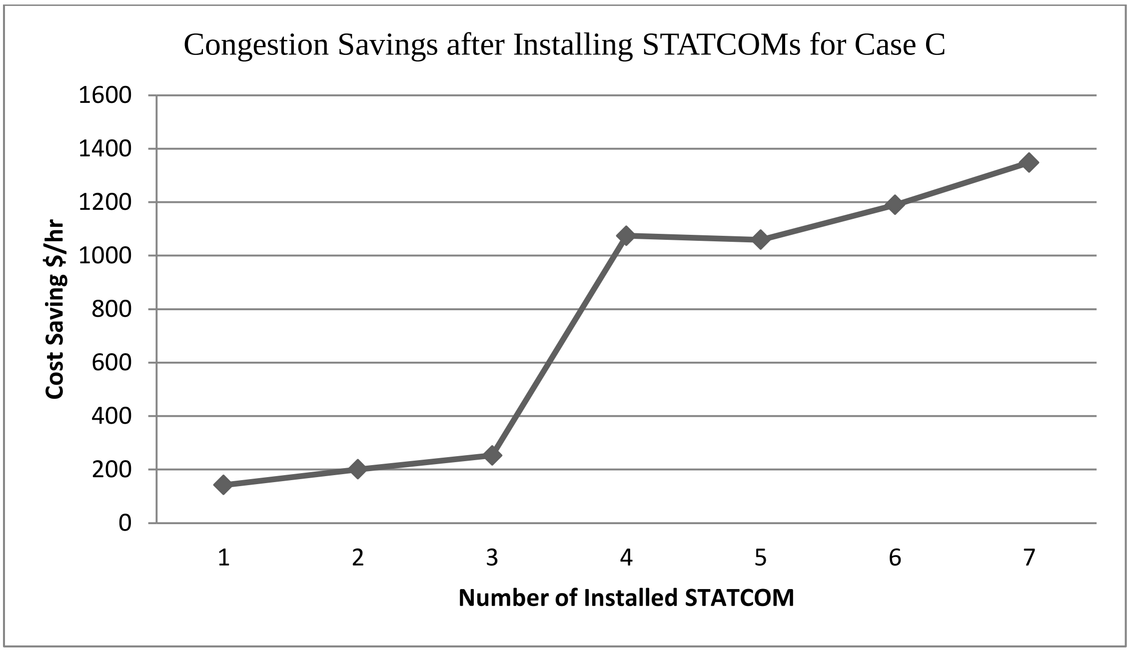


Figure 5.5 Total Savings w.r.t Base Case After Installing STATCOMs for Case C

The results of the objective function is shown in figure 5.6 and show a success in finding the optimum locations and ratings of the four STATCOMs with minimizing reactive power loss in the transmission network. The results suggest that the four optimum locations of the proposed STATCOMs are at bus# 4, 8, 13 and 14. Results are shown in table 5.10

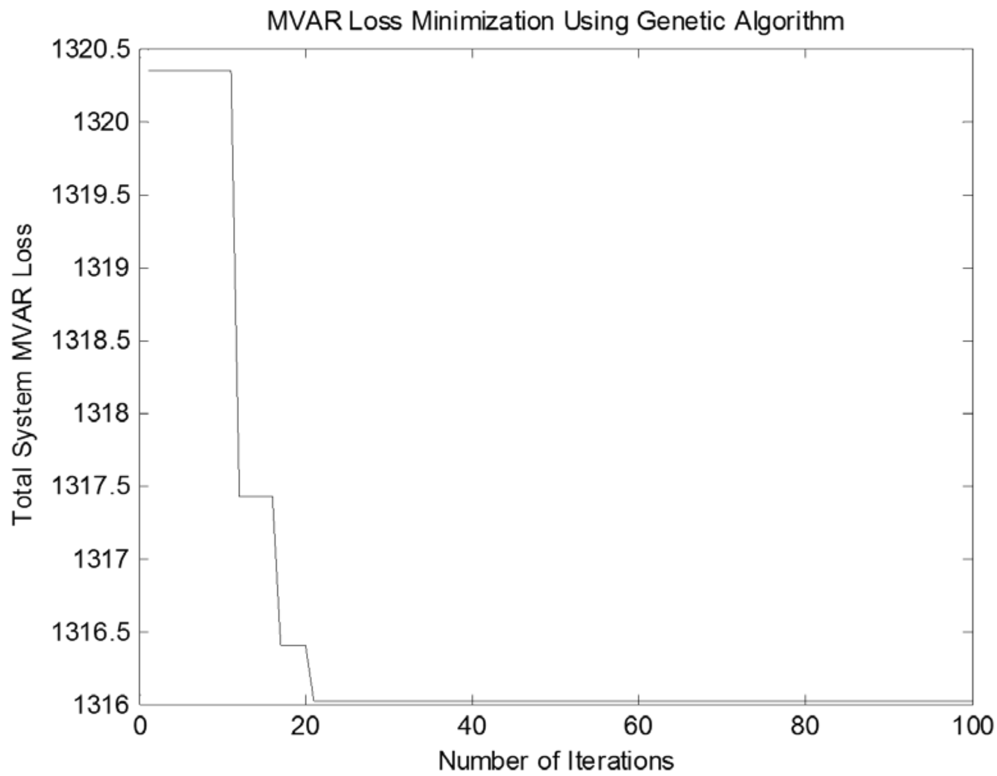


Figure 5.6 Optimization Results of Reactive Power Loss Minimization For Case C

Table 5.10 Optimum Locations and Ratings of STATCOMs for Case C

Bus#	**STATCOM Rating (MVAR)**	**Corresponding MVAR Loss**
4	173.8144	1316.0
8	162.4789	
13	148.1339	
14	193.2805	

The difference made by STATCOMs placement is 49.3 MVAR. Bus results and branch results are shown in table 5.11 and 5.12 respectively.

The results show a total generation of 1,1495.66 MW and 1,464.01 MVAR. The total power cost is 559,853 $/hr with a decrease of 1,074 $/hr (0.2%) in comparison with the case without STATCOM.

Table 5.11 Bus and LMPs Results After Installing STATCOMS For Case C

Bus	**Voltage**		**Generation**		**Load**		**λ**
#	**Mag**	**Angle**	**P(MW)**	**Q(MVAR)**	**P(MW)**	**Q(MVAR)**	**($/MWH)**
1	1.027	-6.205	-	-	151	83	110.915
2	1.029	-5.546	-	-	2400	575	110.778
3	1.05	*0.0	2688.42	178.4	0	0	109.537
4	0.995	-6.048	-	-	100	205	120.691
5	1.039	-3.790	-	-	1600	500	110.407
6	1.05	-1.409	3091	662.62	0	0	109.949
7	1.032	-6.470	-	-	1140	415	110.967
8	1.036	-7.614	-	-	1155	375	111.212
9	1.033	-6.640	-	-	450	140	110.989
10	1.038	-14.638	-	-	550	107	112.663
11	1.05	-4.146	2190.83	252.16	0	0	110.541
12	1.033	-8.923	-	-	2030	297	111.562
13	1.039	-14.494	-	-	545	65	112.705
14	1.029	-13.758	-	-	1200	365	112.549
15	1.05	-1.246	3525	370.83	0	0	109.958
16	1.026	-6.526	-	-	100	50	110.980

Table 5.12 shows the results of branch flow in the transmission network after installing STATCOMs in the system. No overloading situation is observed.

Table 5.12 Branch Flow Results After Installing STATCOMS for Case C

Branch #	From Bus	To Bus	From Bus Injection		To Bus Injection		Losses	
			MW	**MVAR**	**MW**	**MVAR**	**MW**	**MVAR**
31	15	12	786.01	69.8	-780.59	-34.6	5.420	105.94
3	5	2	779.74	207.36	-778.47	-194.45	1.272	25.80
7	5	6	-771.2	-151.01	772.85	165.65	1.652	33.78

5.1.3 STATCOM Installation for Case D

The results showed that the optimum solution which resolves all problems is to install four STATCOMs in the system. Table 5.13 shows the results. The table shows different aspects of system results.

The generation column shows the total power generation produced. As the number of STATCOMs increase, total generation is reduced due to the compensation of STATCOMs. The major effect of STSTCOMs installation can be noticed in MVAR generation reduction of 552.64 MVAR in the optimum solution.

The total active and reactive power losses are shown in the second column of the table. The optimal solution resulted in 845.39 MW loss and 112.5149 MVAR. The installation of STATCOMs resulted in reducing both real and reactive power losses.

The last two columns explain the economical effects after STATCOM installation. Total congestion cost resulted from generation re-dispatch, uplift charges is reduced after the installation of STATCOMs. As a result, STATCOM installation results in cost savings. The optimum solution results in LMPs average of 112.51.

Table 5.13 Results of System Data After Installing Different Number of STATCOMs For Case D

Number of Installed STATCOMs	**Global Contingency (Case D)**					
	Generation		**Losses**		**Cost Diff w.r.t Base Case**	**LMP's**
	MW	**MVAR**	**MW**	**MVAR**	**$/hr**	**$/MWH**
1	11535.17	2801.65	114.169	1963.73	413.88	112.6965
2	11533.37	2533.07	112.372	1929.65	699.26	112.6473
3	11532.64	2372.24	111.640	1915.68	717.94	112.5115
4	11532.01	2279.51	111.005	1903.81	845.39	112.5149
5	11530.70	1894.11	109.700	1879.51	981.92	112.5559
6	11530.76	2041.90	109.758	1879.07	1139.2	112.5559
7	11522.88	1610.56	101.876	1876.59	1189.91	112.1826

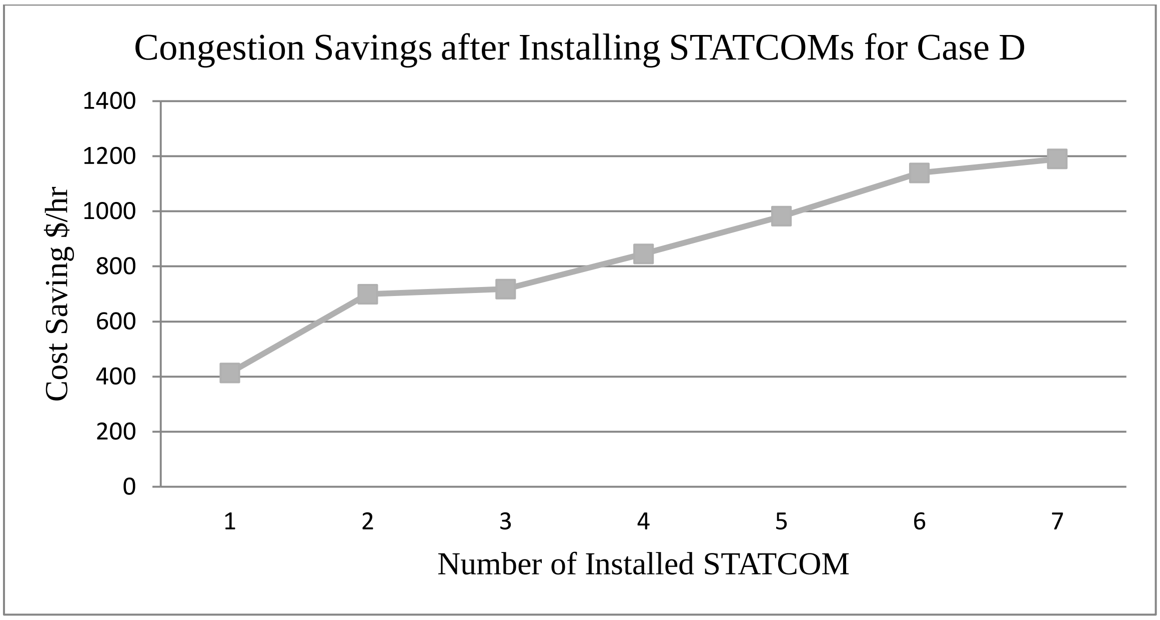


Figure 5.7 Total Savings w.r.t Base Case After Installing STATCOMs for Case D

The results of the objective function is shown in figure 5.8 and show a success in finding the optimum locations and ratings of the four STATCOMs with minimizing reactive power loss in the transmission network. The results suggest that the four optimum locations of the proposed STATCOMs are at bus# 7, 8, 9 and 14. Results are shown in table 5.14.

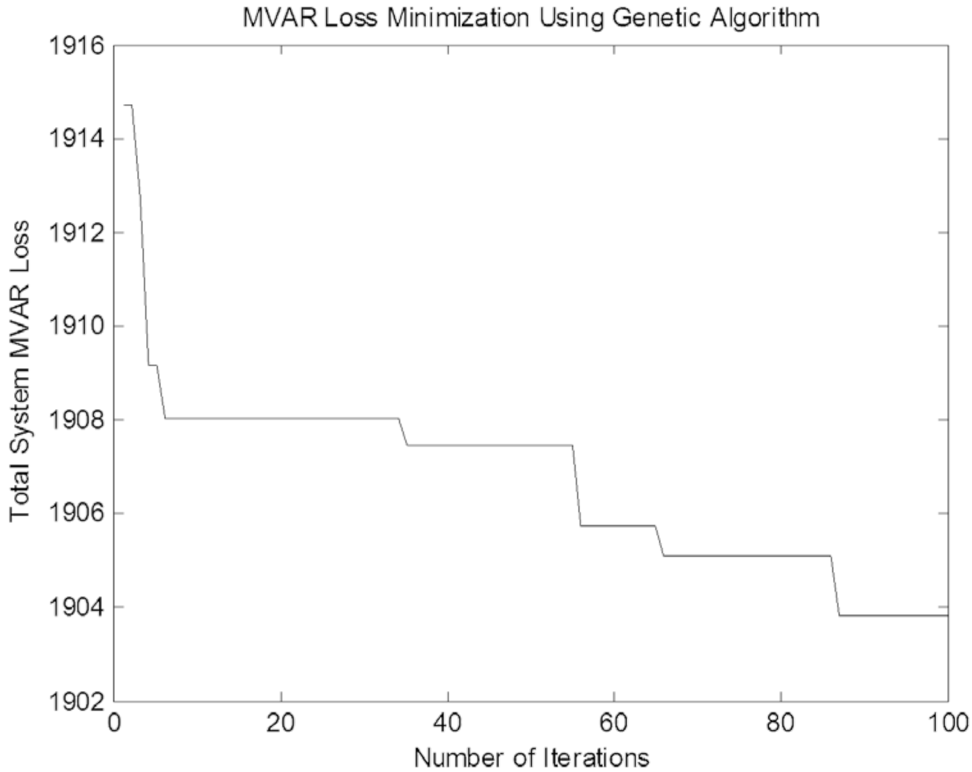


Figure 5.8 Optimization Results of Reactive Power Loss Minimization for Case D

Table 5.14 Optimum Locations and Ratings of STATCOMs for Case D

Bus#	**STATCOM Rating (MVAR)**	**Corresponding MVAR Loss**
7	142.8053	1903.8
8	162.1790	
9	161.0940	
14	136.0252	

The difference made by STATCOMs placement is 49.3 MVAR. Bus results and branch results are shown in table 5.15 and 5.16 respectively.

The results show a total generation of 11,532.01 MW and 2279.51 MVAR. The total power cost is 565,985.25 $/hr.

Table 5.15 Bus and LMPs Results After Installing STATCOMS For Case D

Bus	Voltage		Generation		Load		λ
#	**Mag**	**Angle**	**P(MW)**	**Q(MVAR)**	**P(MW)**	**Q(MVAR)**	**($/MWH)**
1	1.025	-6.296	-	-	151	83	116.382
2	1.027	-5.636	-	-	2400	575	116.235
3	1.05	0	2821.89	309.41	0	0	114.876
4	0.965	-1.137	-	-	35	205	131.709
5	1.037	-3.891	-	-	1600	500	115.842
6	1.05	-1.391	3244.92	806.91	0	0	115.322
7	1.023	-8.533	-	-	1140	415	116.994
8	1.024	-7.391	-	-	1155	375	116.762
9	1.033	-7.991	-	-	450	140	116.819
10	1.025	-14.590	-	-	550	107	118.660
11	1.039	1.986	1940.19	472.67	0	0	98.009
12	1.016	1.963	-	-	2030	297	98.021
13	0.997	-3.771	-	-	545	65	99.171
14	0.993	-2.944	-	-	1200	365	99.015
15	1.05	15.044	3525	690.52	0	0	95.569
16	1.024	-6.619	-	-	100	50	116.452

Table 5.16 Branch Flow Results After Installing STATCOMS for Case C

Branch #	From Bus	To Bus	From Bus Injection		To Bus Injection		Losses	
			MW	**MVAR**	**MW**	**MVAR**	**MW**	**MVAR**
23	8	11	-1626.8	49.13	1639.45	186.30	12.647	268.87
31	15	12	1313.84	239.78	-1298.31	-5.79	15.529	303.55
32	15	12	1152.54	206.96	-1138.83	-7.50	13.709	266.26
33	15	14	1058.62	243.78	-1041.24	-17.31	17.381	339.70

5.2 Revenue Rate and Congestion Cost Saving

Since STATCOMs are used in the case of congestion period in the study, the revenue ratio is calculated in a ratio of $/hr for each case. Hence, the total payback period will be the ratio multiplied by the time duration, which STATCOMs were in service, on which the system is under congestion situation. Table 5.13 shows the revenue rate of each case of contingency analysis.

Table 5.17 Revenue Rate of Each Case of Contingency Analysis After STATCOM Installation

Congestion Case	Revenue Rate ($/hr)
Removal of Most Loaded Line (Case A)	1081.93
Removal of Two Most Loaded Lines (Case B)	1138.93
Minimum Cost Generating Plant Reduction by 25% (Case C)	1074.43
Global Contingency	845.39

The maximum capacity of STATCOM in the study is 200 MVAR. Thus;

200 MVAR x 50,000 $/MVAR = 10,000,000$ is the cost of one STATCOM

So, the total capital cost of four STATCOMs = 40,000,000$

Thus, the annual cost of STATCOMs based on 20 years of lifetime = 2000,000$

Table 5.14 shows Annual Congestion Cost Saving of Each Case of Contingency Analysis for installing four STATCOMs in the system under study based on study results.

Table 5.18 Annual Congestion Cost Saving of Each Case of Contingency Analysis

Congestion Case	Annual Congestion Cost Savings ($)
Removal of Most Loaded Line (Case A)	9,347,875
Removal of Two Most Loaded Lines (Case B)	9,840,355
Minimum Cost Generating Plant Reduction by 25% (Case C)	9,2830,75
Global Contingency	7,304,169
No Contingency	2,257,200

Although congestion cases occur usually in the power system, they are rectified after sometime. So, the state of contingency will not be a continuous state of the system. Hence, to calculate an estimation of annual cost saving, a percentage will be assigned to each case of the contingency depending on the chance of occurrence. The percentage will be divided as the follow:

- 60 percent for no contingency case.
- 20 percent for case A.
- 10 percent for case B
- 8 percent for case C. and
- 2 percent for case D.

The annual congestion saving cost then will be:

(0.6)x(2257200) + (0.2)x(9,347,875) + (0.1)x(9,840,355) + (0.08)x(9,283,075) + (0.02)x(7304169) = 5,096,660$/year. This shows sufficient revenue based on the capital cost of desired number of STATCOMs.

CHAPTER 6

6. STUDIES ON THE APPLICATION OF STATCOM AND SVC

6.1 Comparison between STATCOM and SVC in Congestion Management

In order to assess the performance of STATCOM in congestion management, a comparison is made with an alternative type of FACTS, that is: Static Var Compensator (SVC). The same approach is used to install SVCs in steady state and maintain the operation for the contingency on the same system under study.

Case A: Removal of Most Loaded Line.

In this case, the optimum number of STATCOMs is found to be four with a total 1665.82 MVAR loss. On the other hand, a total of 5 SVCs are required for the same case with a 1,711.05 MVAR loss.

Furthermore, the effect of installing STATCOMs into the system result in saving re-dispatch cost by 1081.13 $/hr compared to no FACTS installed. However, utilizing SVCs in system under study resulted in 972.17 $/hr reduction in generation re-dispatch prices compared to the case with no FACTS installed. Figure 6.1 shows a comparison in total savings after installing STATCOMs and SVCs for case A.

It can be concluded that it requires more number of SVCs to be installed in the network in order to obtain a competitive results with lower number of STATCOMs.

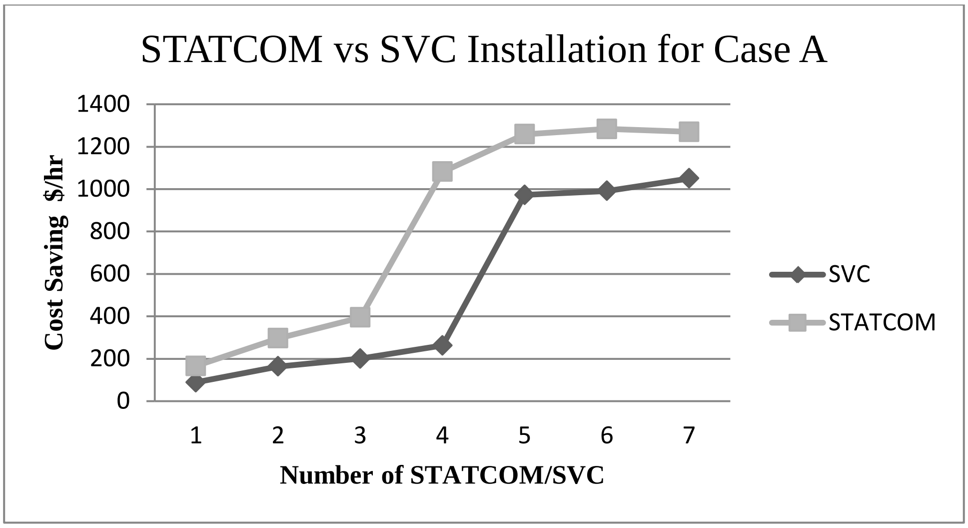


Figure 6.1 Effect of STATCOM vs. SVC Installation on Total Cost Reduction For Case A

Case B: Removal of Two Most Loaded Lines.

In this case, the optimum number of STATCOMs was found to be four with a total 2229.16 MVAR loss. On the other hand, a total of 6 SVCs installation are required for the same case with a 2,272.17 MVAR loss.

Moreover, the effect of installing STATCOMs into the system result in decreasing generation re-dispatch cost by 1138.93 $/hr compared to no FACTS installed. However, utilizing SVCs in system under study resulted in 952.06 $/hr reduction in generation re-dispatch prices compared to the case with no FACTS installed. Figure 6.2 shows a comparison in total saving after installing STATCOMs and SVCs for case B.

The decrease in transmission network capacity in this case was due to eliminating the most two loaded lines from the grid. This led to overload several branches to compensate the eliminated lines. Consequently, a voltage decrement occurs at several buses due to the lack of reactive power in the system. This explains the need to MVAR injection to the system which was more sufficient by utilizing STATCOMS.

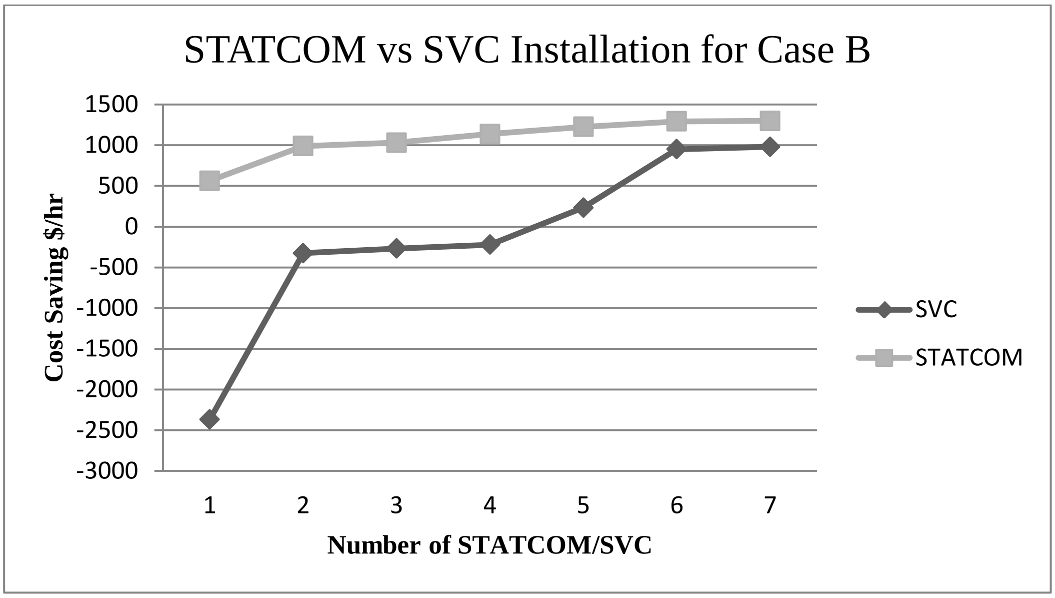


Figure 6.2 Effect of STATCOM vs. SVC Installation on Total Cost Reduction For Case B

Case C: Least Cost Generation Reduction.

In case of reducing the generation capacity of the least cost generation plant, the optimum number of STATCOMs is found to be four with a total 1316.02 MVAR loss. On the other hand, a total of 4 SVCs units in the same case is required with a 1,337.4 MVAR loss.

The effect of installing STATCOMs into the system result in decreasing generation re-dispatch cost by 1074.43 $/hr compared to no FACTS installed. On the other hand, utilizing SVCs in system under study result in 998.82 $/hr reduction in generation re-dispatch prices compared to the case with no FACTS installed. Figure 6.3 shows a comparison between of STATCOMs and SVCs after removing most loaded line from the transmission system under study.

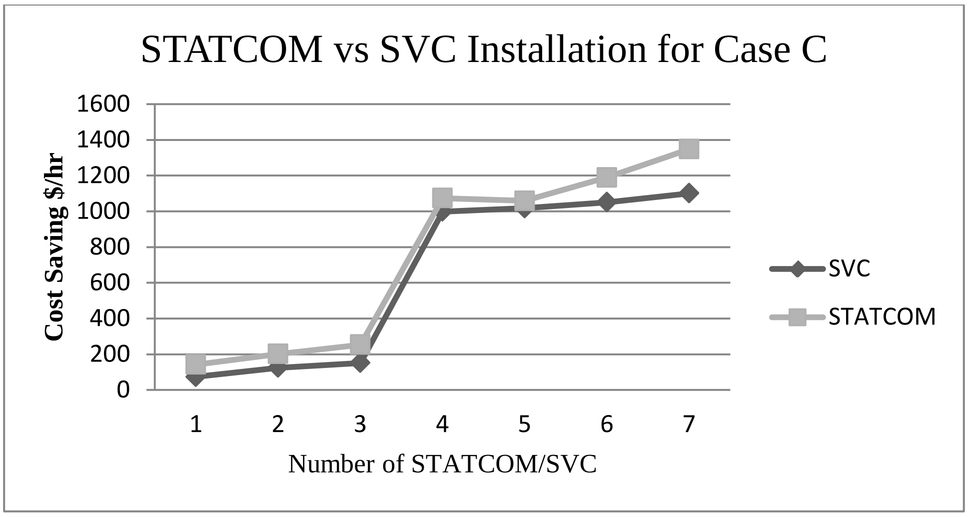


Figure 6.3 Effect of STATCOM vs. SVC Installation on Total Cost Reduction For Case C

It can be noticed in Case C that STATCOM and SVC installation have approximately the same results. This result can be predicted since in this case the effect of reducing generation will result in LMP effect only. No system disturbance will occur due to the availability of satisfying generation capacity.

Table 6.1 shows a summary of the study results for STATCOM and SVC comparison for the three cases.

Table 6.1 STATCOM vs. SVC Comparison Study Results

Contingency Case	**MVAR Loss**		**Cost Reduction w.r.t No FACTS ($/hr)**		**Required Number**	
	STATCOM	**SVC**	**STATCOM**	**SVC**	**STATCOM**	**SVC**
Case A	1665.82	1711.05	1081.13	972.17	4	5
Case B	2229.16	2272.17	1138.93	952.06	4	6
Case C	1316.02	1337.4	1074.43	998.82	4	4

6.2 Comparison of STATCOM Studies in Congestion Management [12]

An approach to maximize the benefits of FACTS installation in power system for an efficient solution to congestion management in bilateral electricity markets is presented in [12]. Minimizing congestion cost was examined using the optimum location and ratings of installing STATCOM and UPFC about congested lines. Preliminary results have shown that the method is able to effectively determine the optimum location to minimize congestion costs using a 4-bus system. The study case has indicated that a STATCOM is a viable economic solution to the congestion management problem in bilateral electricity market environments.

The 4-bus system was under study of congestion management using STATCOM devices. The approach used for utilizing STATCOM in congestion management is as follows:

Step 1. Solve congestion management problem without STATCOM.

Step 2. Active power generation levels and total cost and identification of congested lines are determined.

Step 3. Determine the optimal rating of STATCOM at each location.

Step 4. Rating of STATCOM, total cost and change in total cost with respect to step 1 is calculated.

Table 6.2 shows the results of percentage of reduction of the total cost with respect to no STATCOM installed in the system.

Table 6.2 Results for percentage Savings of Total Savings Comparing to no STATCOM from [12]

STATCOM Location	**% Savings in Total Cost w.r.t no STATCOM**	**STATCOM Rating (MVAR)**
No STATCOM	0%	N/A
Bus 4	43%	225
Bus 2	83%	130

On a larger system scale, the results of this thesis show approximately same results as reference [12]. The study results show that the congestion cost saving after utilizing STATCOMs in a congested transmission network is about 80% . Table 6.3 shows percentage of total cost saving after utilizing STATCOM in the transmission network under study with optimum number, location and rating.

Table 6.3 Thesis results percentage of Savings of Total Cost Compared to no STATCOM

Congestion Case	**% Saving of Total Cost w.r.t no STATCOM**	**STATCOM location and Rating**
No STATCOM	0%	N/A
Most Loaded Line Removal	79.76%	4 STATCOMs in different Locations with a maximum capacity of 200 MVA
Two Most Loaded Lines Removal	83.96%	
Minimum Cost Generating Plant Reduction by 25%	79.21%	

6.3 Reducing the Number of STATCOMs

Another economical approach is under study is to reduce the number of STATCOMs that will be installed. This approach may result in resolving the problem of congestion relief besides reducing the capital cost of STATCOMs. As a result, the revenue period for investing in the transmission network will be reduced.

The optimum solution of contingency analysis was found to be a total number of four STATCOMs with a maximum rating of 200 MVAR capacities to be installed in different locations. The number of STATCOMs is reduced to two units with 400 MVAR ratings. The same optimization approach is used to obtain the optimum results.

Although the total MVAR loss is slightly decreased when installing the larger STATCOMs, the total cost price has a significant difference between the two cases. This indicates that locating STATCOM in a transmission network would result in better enhancement in generation re-dispatch stage. Table 6.4 shows a comparison between the two cases.

Table 6.4 Comparison between the Effect of Installing 4 STATCOMs with Optimum Location and Ratings and two STATCOMs with a Higher Ratings

Contingency Case	**4 STATCOMs with 200 MVAR Capacity Each**		**2 STATCOMs With 400 MVAR Capacity Each**	
	MVAR Loss	**Total Savings w.r.t No STATCOM \$/hr**	**MVAR Loss**	**Total Savings w.r.t No STATCOM \$/hr**
Removal of Most Loaded Line	1687.16	1081.93	1713.33	260.56
Removal of two Most Loaded Lines	2229.16	1138.93	2309.91	387.73
Minimum Cost Generating Plant Reduction by 25%	1316.02	1074.43	1328.28	230.69

CHAPTER 7

7. CONCLUSION AND FUTURE WORK

7.1 Conclusion

In this thesis, congestion relief in power transmission network using STATCOM is proposed based on technical and economic constraints.

A case study of a typical real system is used to perform the study. Contingency analysis was performed that would be considered by Independent System Operator. First, a case of most loaded line removal was examined. A further contingency was simulated by the removal of two most loaded lines. Finally, a partial reduction of power generation capacity is tested.

The results show that the Congestion Revenues is forming most of the total congestion cost. Total cost savings was found to be 79.76% in removal of most line case. In two line removal case, Total cost savings resulted in 83.96% of the total congestion cost. In generation reduction case, the Total cost savings were found to be 79.21% of congestion cost.

The congestion cost saving is found depending on the time duration that STATCOMs were in service. The results showed that in one line removal case the cost saving rate is 1,081.93 $/hr. In two lines removal case, the payback rate was found to be 1,138.93 $/hr. The payback rate in generation reduction case was found to be 1,074.43 $/hr.

Study results show utilizing STATCOM, in congested network, may be more efficient than SVC. The number of used STATCOMs in all cases of contingency analysis resulted in four STATCOMs. On the other hand, different numbers of SVCs were used depending on the contingency case.

Finally, reducing the number of STATCOMs with a larger capacity did not proof efficiency in term of congestion cost minimization. This indicates that the location at which STATCOM is installed has a critical effect on system security and reliability.

7.2 Future Work

It is recommended in future work to consider FACTS controllers coordination in case of congestion. Furthermore, combination of series and shunt compensation could result in more efficient results due to the increment of transmission capability due to the series compensation. Also, further factors could be considered in congestion costs such as environmental effects, such as CO_2 emissions costs and different type of fuel pollution costs. Furthermore, other factors could be considered in transmission uplift charges like transformer overloading, which would affect transformer lifetime. Moreover, the strategic bid by independent power producers is of great impact on the congestion costs.

CHAPTER 8

8. REFERENCES

[1] Ettore Bompard, Pedro Correia, George Gross, and Mikael Amelin, "A Comparative Analysis of Congestion Management Schemes under a Unified Framework", IEEE transaction on Power System Vol. 18 No 1, pp 346-352, Feb 2003

[2] F.A Wolak and R.H Patrik, "The Impact of Market Rules and Market Structure on the Price Determination Process in the England and Wales Electricity Market", POWER Report. PWP-047, University of California Energy Institute, Berkley, April 1997.

[3] PJM Interconnection, L.L.C, "Operating Agreement", June 1997, http://www.pjm.com/.

[4] Norwegian Electric Power Research Institute, "Deregulation of Nordic Power Market: Implementation and Experiences, 1991-1997", Technical Report, November 1997.

[5] California ISO, "ISO Tariff", April 1998, http://www.caiso.com/.

[6] G. Hingorani and L. Gyugyi, Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems. New York, IEEE Press, 2000.

[7] L. Gyugyi, "Dynamic compensation of AC transmission lines by solid-state synchronous voltage sources," IEEE Transactions on Power Delivery, vol. 9, no. 2, pp. 904-911, Apr. 1994.

[8] Saranjeet, "Evolutionary Algorithm Assisted Optimal Placement of FACTS Controllers in Power System", M.S. Thesis for Master Degree in Electrical Engineering in Power Systems & Electric Drives, Thapar University, Patiala, July 2009.

[9] Schauder C., Gernhardt M., Stacey E., Lemak T., Gyugyi L., Cease T. W., and Edris A., Operation of ±100 MVAr TVA STATCON, IEEE Transactions on Power Delivery, Oct 1997, Vol.12, No. 4, pp.1805–1811.

[10] Keshi Reddy Saidi Reddy, Narayana Prasad Padhy, and R.N. Patel, “Congestion Management in Deregulated Power System using FACTS Devices”, IEEE 0-7803-9525-5/06/$20.00, 2006.

[11] Naresh Acharya, and N. Mithulananthan, “Locating series FACTS devices for congestion management in deregulated electricity markets”, Electric Power System Research 77, pp. 352-360, 2007

[12] X. P. Zhang, B. Chong, K. R. Godfrey, L.Yao, M. Bazargan and L. Schmitt, “Management of Congestion Costs Utilizing FACTS Controllers in a Bilateral Electricity Market Environment”, Germany Spring 2006.

[13] Karami, M. Rashidinejad, and A. A. Gharaveisi, “Voltage Security Enhancement and Congestion Management Via STATCOM & IPFC Using Artifical Intelligence”, Iranian Jornal of Science & Technology, Transaction B, Engineering, Vol. 31, No. B3, pp 289-301, Iran 2007.

[14] Ray D. Zimmerman, Carlos E. Murillo-Sanchez, “MATPOWER 4.1 User’s Manual”, Power System Engineering Research Center, University of Wisconsin, December 2011

[15] M. Judite Ferreira, Zita A. Vale, and Jose Cardoso, “A Congestion Management and Transmission Price Simulator for Competitive Electricity Markets”, IEEE 1-4244-1298-6/$25.00, 2007.

[16] Zhiping Yang, Chen Shen, Mariesa L. Crow, Lingli Zhang, “An Improved STATCOM Model For Power Flow Analysis”, IEEE 0-7803-6420-1/00/$10.00, 2000.

[17] G.A Adepoju, O.A. Komolafe, “Analysis and Modeling of STATCOM: A Comparison of Power Injection and Current Injection Models in Power Flow Study”, International Journal of Advanced Science and Technology, Vol.36, November 2011.

[18] A. Sode-Yome, N. Mithulananthan, K. Lee, “Static Voltage Stability Margin Enhancement Using STACOM, TCSC and SSSC”, Transmission and Distribution Conference and Exhibition, Asia and Pacific, pp.1-5, 2005.

[19] Claudio A. Canizares, Sameh K. Kodsi, “Dynamic Versus Steady-State Modeling of FACTS Controllers in Transmission Congestion”, Technical Report, University of Waterloo, 2007.

[20] Juan Dixon, Luis Moran, Jose Rodriguez, Ricardo Domke, “Reactive Power Compensation Technologies, State-of-the-Art Review”, Invited paper IEEE, 2006.

[21] Mark Ndubuka NWOHU, “Voltage Stability Improvement Using Static Var Compensator in Power Systems”, Leonardo Jornal of Sciences, pp. 167-172, June 2009.

[22] Bernard C. Lesieuture, Joseph H. Eto, “Electricity Transmission Congestion Costs: A Review of Recent Reports”, University of California Berkeley, 2003, http://eetd.lbl.gov/ea/EMS/EMS_pubs.html.

[23] Arthit Sode-Yome, Nadarajah Mithulananthan, “An Economical Generation Direction for Power System Static Voltage Stability”, Electric Power System Research 76, pp. 1075-1083, March 2006.

[24] James Daniel Weber, “Implementation of a Newton-Based Optimal Power Flow Into A Power System Simulation Environment”, Thesis Report, pp. 10-14, University of Wisconsin- Platteville, 1995.

[25] Sawan Sen, Priyanka Roy, Abhijit Chakrabarti, Samarjit Sengupta, "Generator Contribution Base Congestion Management Using Multiobjective Genetic Algorithm", Technical Report, TELKOMNIKA, Vol.9, No.1, pp. 1-8, Bengal Engineering and Science University, April 2011.

[26] Mohsen Gitzadeh, Mohsen Kalantar, "Genetic Algorithm-Based Fuzzy Multi-Objective Approach to Congestion Management using FACTS Devices", Electr Eng DOI 10.1007/s00202-008-0105-7, Springer-Verlage, 2008.

[27] M.I. Almoush, S.M. Shahidehpour, "Fixed Transmission Rights for Zonal Congestion Management", IEEE Proc-Gen, Trans. Distrib., vol. 146, No.5, September 1999.

[28] Terje Gjengedal, Jan Ove Gjerde, Roger Flolo, "Transmission Open Access; Management, Operation and Pricing", IEEE 0-7803-31-09-5/96, 1996.

[29] Charles Raja, P. Venkatesh, and B. V. Manikandan, "Transmission Congestion Management in Restructured Power System", IEEE 978-1-4244-7926-9/11/S26.00, 2011.

[30] John W. Pope, Fellow," Congestion Management In Regional Transmission Organization", Porto Power Tech Conference, September 2001

[31] R.S. Fang, A.K. David, "Transmission Congestion Management in an Electricity Market", IEEE Transactions on Power Systems, Vol. 14, August 1999.

[32] Chai Chompoo-inwai, Chitra Ying vivatanaong, pradit Fungfoo, and Wei-Jen Lee, "Transmission Congestion Management During Transition Period of

Electricity Deregulation in Thailand", IEEE transactions on industry applications, Vol.43, No.6, November/December 2007.

[33] Richard D. Christie, Bruce F. Wollenberg, Ivar Wangensteen, "Transmission Management in the Deregulated Environment", Proceedings of the IEEE vol. 88, no.2, February 2000.

[34] G. Hingorani and L. Gyugyi, Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems. New York, IEEE Press, 2000.

[35] M. A. Rahim, Ismail Mursirin, Izham Zainal Abidin, and Muhammad Murtadha Othman, "Contingency Based Congesiton Management and Cost Minimization Using Bee Colony Optimization Technique", IEEE PEC Kuala Lumpur, 2010.

[36] Nordanlycke, G. Bossert, and H. Glavitsch, "Security and Congestion Management Tool for the Use in Extended Transmission Systems", IEEE 978-1-4244-2190/07/$25.00, 2007.

[37] Yi Tang, Hui Xu, and Qiulan Wan, "Research on the Application of Financial Transmission Right in Congestion Management", DRPT, Nanjing China, April 2008.

[38] Shangyou Hao, "Decentralized Approach to Intermarket Congestion Management", IEEE 0885-8950/$20.00, 2005.

[39] Xusheng Yang, Wanxing Sheng, Xiaoli Meng, and Sunan Wang, "A New Solution for Multi-Region Transmission Congestion Management", IEEE 0-7695-2528-8/06 $20.00, ISDA 2006.

[40] Osman Bulent Tor, Mohammad Shahidehpour, "Transmission Management and Planning: The aftermath of Turkish Electricity Restructuring", IEEE 1-4244-0228-X/06/$20.00, 2006.

[41] T. Niimura, and Y. Niu, "Transmission Congestion Relief by Economic Load Management", IEEE 0-7803-7519-X/02/417.00, 2002.

[42] Jian Yang, and Max D. Anderson, "Tracing the Flow of Power in Transmission Networks for Use-of-Transmission-System Charges and Congestion Management", IEEE 0-7803-4403-0/98/$10, 1998.

[43] K. Okada, M. Kitamura, H. Asano, M. Ishimarum and R. Yokoyama, "Cost-Benefit Analysis of Reliability Management by Transmission Expansion Planning in the Competitive Electric Power Market", IEEE 0-7803-6338-8/$10, 2000.

[44] Richard D. Tabors, "Transmission System Management and Pricing: New Paradigms and International Comparisons", IEEE 0885-8950/94/$40.00, 1993.

[45] Chien-Ning Yu, and Marija D. Ilic, "Congestion Clusters-Based Markets for Transmission Management", IEEE 0-7803-4403-0/98/$10.00, 1998.

[46] J. Hazra, A. K. Sinha, and Y.Phulpin, "Congestion Management using Generation Rescheduling and/or Load Shedding of Sensitive Buses", IEEE Third International Conference on Power Systems, India, December 2009.

[47] Mary Ellen Paravalos, Mark Brackley, and Graham Hathaway, "Congestion Management Techniques in the UK and US - Approaches and Results", IEEE 0-7803-9191-8/05/$20.00, 2005.

[48] F. Spaan, P. van den Heuvel, J. de Geus, K. Hommes, S. A. B. de Almedia de Graaff, R. Besselink, D. Klaar TenneT TSO B.V The Netherlands,

"Congestion Management implemented in the Dutch System by using market principles: a practical example from the TSO perspective", 21, rue d'Artois, F-75008 Paris, CIGRE 2012.

[49] Constantin Barbulescu, Petru Dan Cristian, Florin Solomonesc, and Stefan Kilyeni, "Congestion Management Driven Transmission Expansion Planning", 46th International Universities' Power Engineering Conference, 2011.

[50] Wang, C.W. Yu, A.K. David, C.Y. Chang, C.T. Tse, "Transmission Congestion Management in Restructured Electricity Supply", Proceedings in 5th International Conference on Advances in Power System Control, Operation and Management, Hong Kong, October 2000

9. APPENDIX A

BUS DATA

#	Type	Pd	Qd	Vm	Va	Base KV	Vmax	Vmin	Zone
1	1	151	83	1.02	-4	380	1.05	0.95	1
2	1	2400	575	1.01	-4.2	380	1.05	0.95	1
3	3	0	0	1.04	0	380	1.05	0.95	1
4	1	35	205	1.04	-2.7	380	1.05	0.95	1
5	1	1600	500	1.02	-2.7	380	1.05	0.95	1
6	2	0	0	1.03	-0.5	380	1.05	0.95	1
7	1	1140	415	1.03	-5.8	380	1.05	0.95	1
8	1	1155	375	1.02	-7.2	380	1.05	0.95	1
9	1	450	140	1.03	-5.8	380	1.05	0.95	1
10	1	550	107	1.03	-14.8	380	1.05	0.95	1
11	2	0	0	1.03	-3.5	380	1.05	0.95	1
12	1	2030	297	1.02	-4.8	380	1.05	0.95	1
13	1	545	65	1.02	-11.3	380	1.05	0.95	1
14	1	1200	365	1.03	-11.2	380	1.05	0.95	1
15	2	0	0	1.04	-3.7	380	1.05	0.95	1
16	1	100	50	1.02	-4.1	380	1.05	0.95	1

GENERATOR DATA

Bus#	Pg	Pq	Qmax	Qmin	Vg	Mbase	Status	Pmax	Cost ($/MW)
3	3000	642	1312	-1096	1.015	100	1	3000	0.02
6	3500	405.5	2620	-1590	1.045	100	1	3500	0.0175
11	2700	704.8	1312	-1096	1.03	100	1	2700	0.025
15	4700	405.5	1230	-870	1.03	100	1	3500	0.00834

BRANCH DATA

#	From Bus	To Bus	R	X	B	Rate MVA	Ratio	Angle	Status	Ang min	Ang max
1	1	16	0.00059	0.01192	0.35210	1650	1	1	1	-360	360
2	1	16	0.00059	0.01192	0.35210	1650	1	1	1	-360	360
3	5	2	0.00021	0.00426	0.12065	1650	1	1	1	-360	360
4	5	2	0.00021	0.00426	0.12065	1650	1	1	1	-360	360
5	5	3	0.00121	0.02446	0.72260	1650	1	1	1	-360	360
6	5	3	0.00121	0.02446	0.72260	1650	1	1	1	-360	360
7	5	6	0.00029	0.00593	0.17540	1650	1	1	1	-360	360
8	5	6	0.00029	0.00593	0.17540	1650	1	1	1	-360	360
9	5	6	0.00029	0.00593	0.17540	1650	1	1	1	-360	360
10	5	6	0.00029	0.00593	0.17540	1650	1	1	1	-360	360
11	5	4	0.00144	0.02908	0.85910	1650	1	1	1	-360	360
12	5	4	0.00144	0.02908	0.85910	1650	1	1	1	-360	360
13	5	9	0.00129	0.02610	0.77170	1650	1	1	1	-360	360
14	5	9	0.00129	0.02610	0.77170	1650	1	1	1	-360	360
15	2	3	0.00117	0.01920	0.66605	1650	1	1	1	-360	360
16	2	3	0.00117	0.01920	0.66605	1650	1	1	1	-360	360
17	2	1	0.00050	0.00972	0.34110	1650	1	1	1	-360	360
18	2	1	0.00050	0.00972	0.34110	1650	1	1	1	-360	360
19	14	13	0.00059	0.0116	0.40932	1650	1	1	1	-360	360
20	8	3	0.00148	0.02432	0.84320	1650	1	1	1	-360	360
21	8	10	0.00242	0.04752	1.66760	1650	1	1	1	-360	360

22	8	10	0.00242	0.04752	1.66760	1650	1	1	1	-360	360
23	8	11	0.00050	0.01063	0.31440	1650	1	1	1	-360	360
24	8	7	0.00021	0.00427	0.12630	1650	1	1	1	-360	360
25	9	7	0.00076	0.01549	0.45770	1650	1	1	1	-360	360
26	9	7	0.00076	0.01549	0.45770	1650	1	1	1	-360	360
27	3	7	0.00153	0.03098	0.91540	1650	1	1	1	-360	360
28	11	12	0.00100	0.01820	0.62940	1650	1	1	1	-360	360
29	11	12	0.00100	0.01820	0.62940	1650	1	1	1	-360	360
30	11	14	0.00160	0.3230	0.95420	1650	1	1	1	-360	360
31	15	12	0.00095	0.01857	0.65186	1650	1	1	1	-360	360
32	15	12	0.00109	0.02117	0.62613	1650	1	1	1	-360	360
33	15	14	0.00158	0.03088	1.08390	1650	1	1	1	-360	360
34	15	7	0.00076	0.01549	0.45770	1650	1	1	1	-360	360
35	15	7	0.00076	0.01549	0.45770	1650	1	1	1	-360	360
36	13	12	0.00122	0.02398	0.84137	1650	1	1	1	-360	360

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